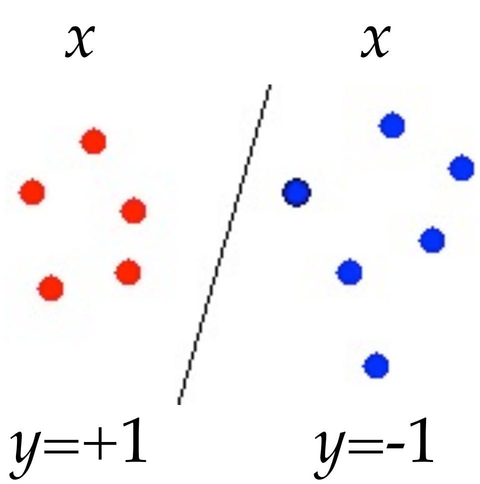
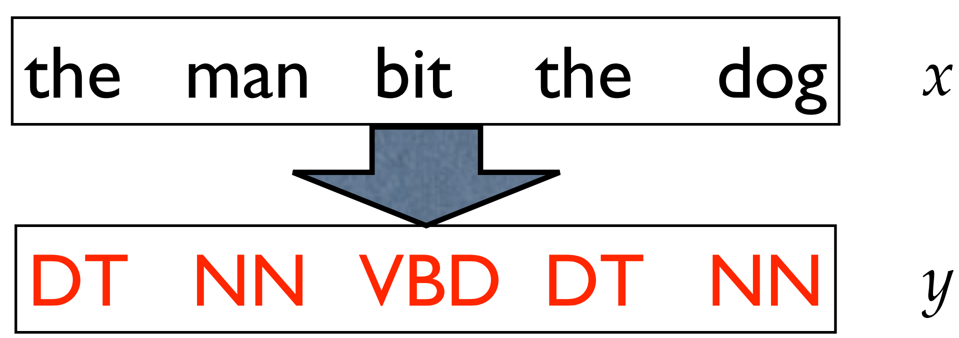
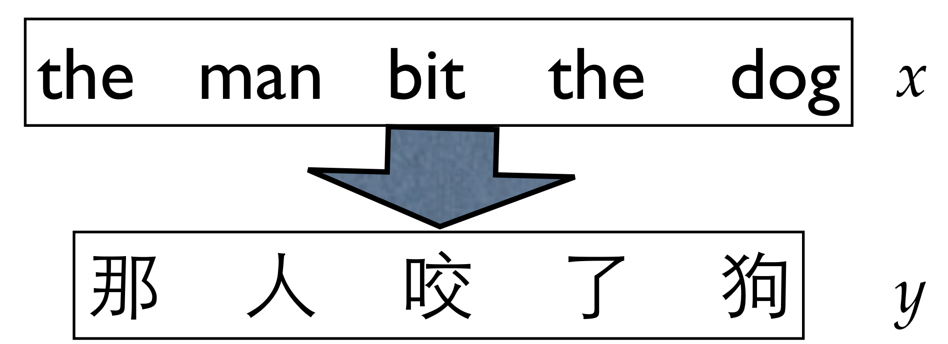
Structured Perceptron with Inexact Search







Liang Huang Suphan Fayong Yang Guo

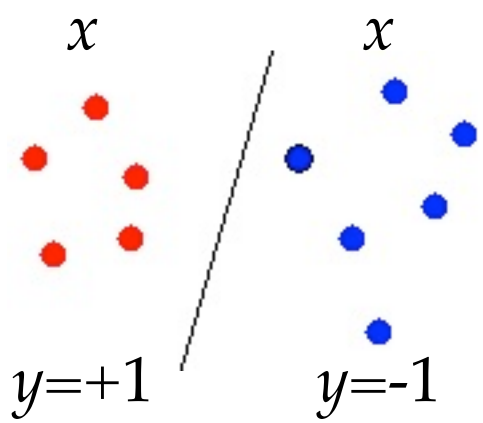
Information Sciences Institute

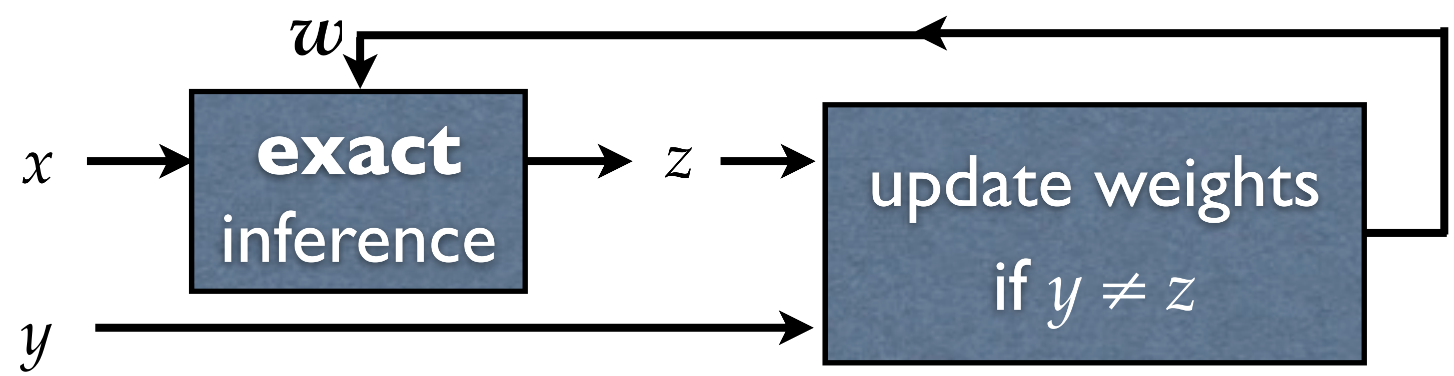
University of Southern California

NAACL 2012 Montréal June 2012

Structured Perceptron (Collins 02)

binary classification





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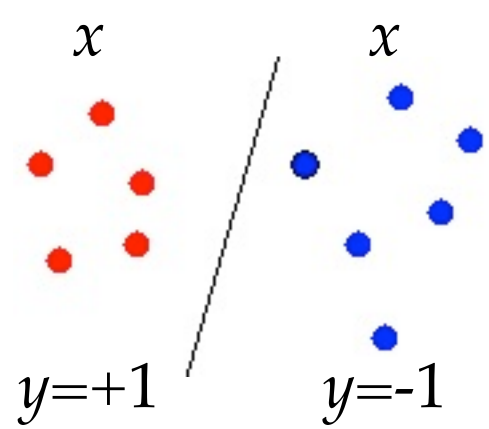
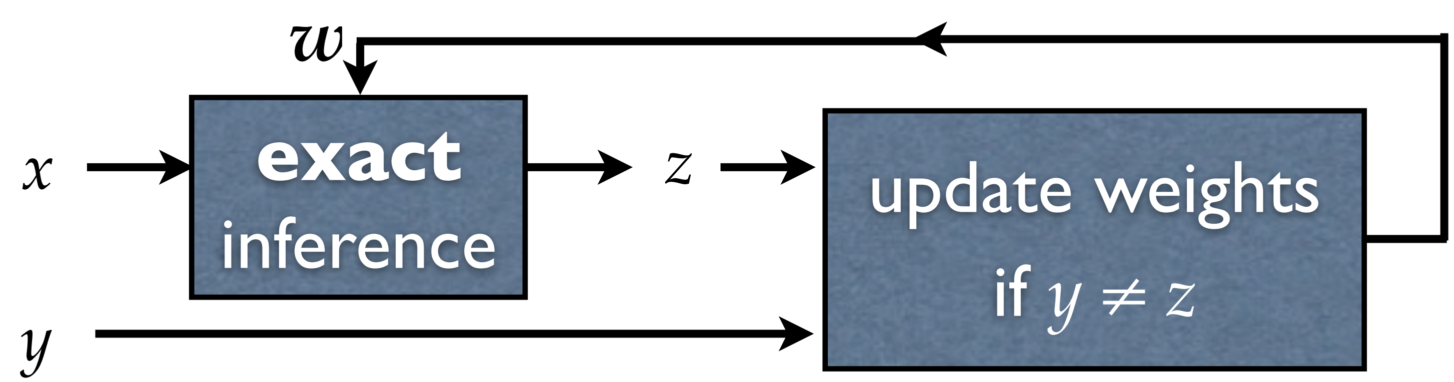
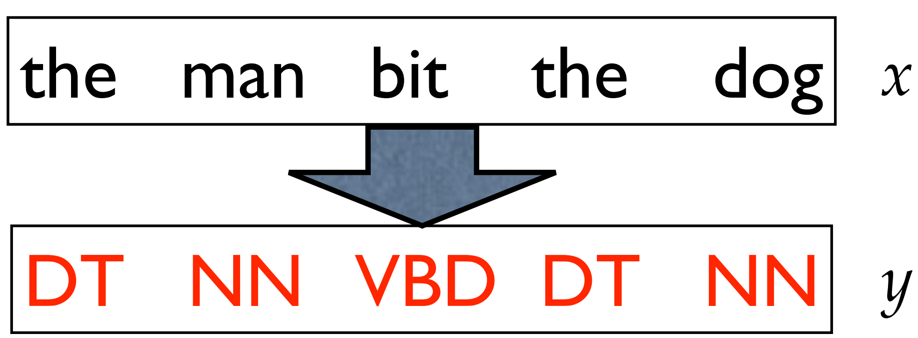




structured classification



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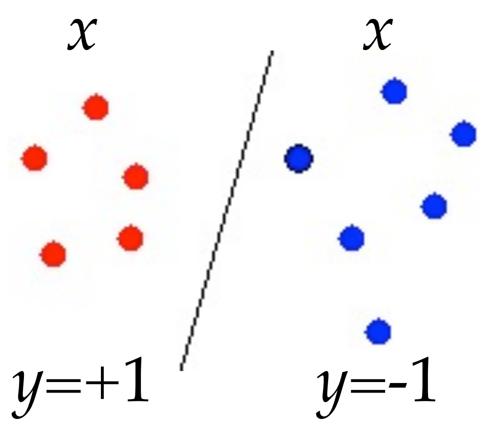

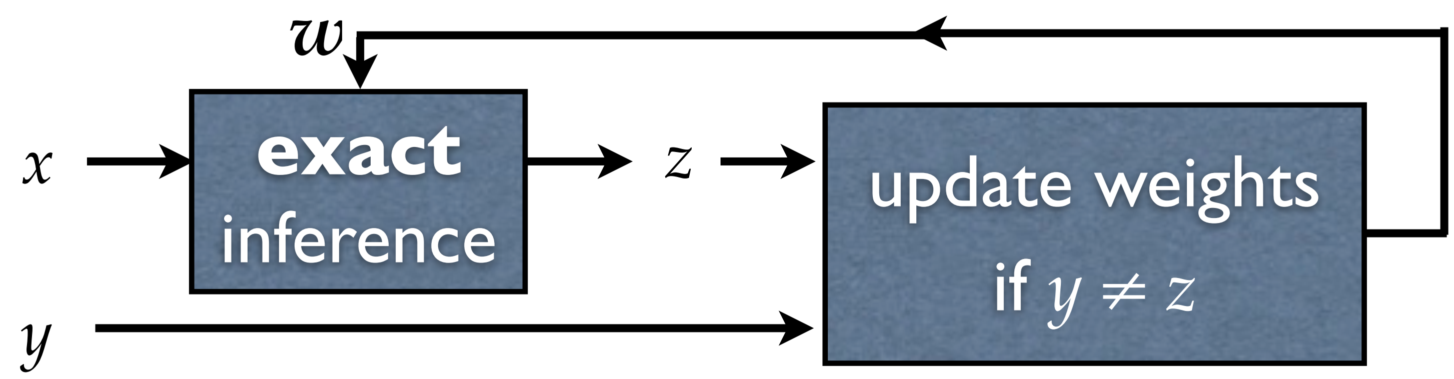

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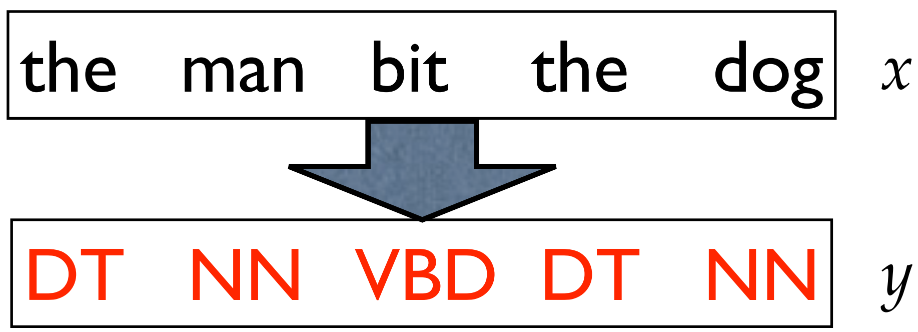

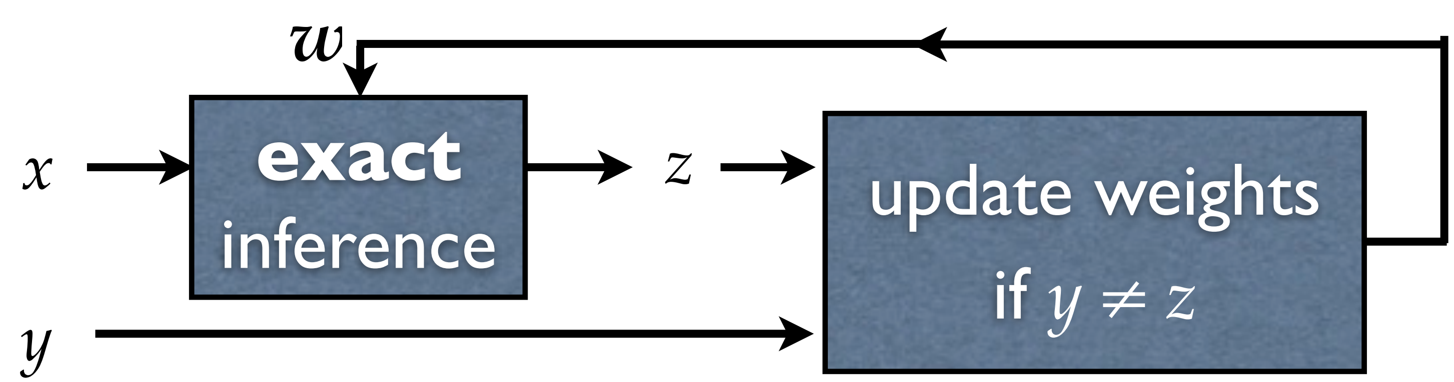

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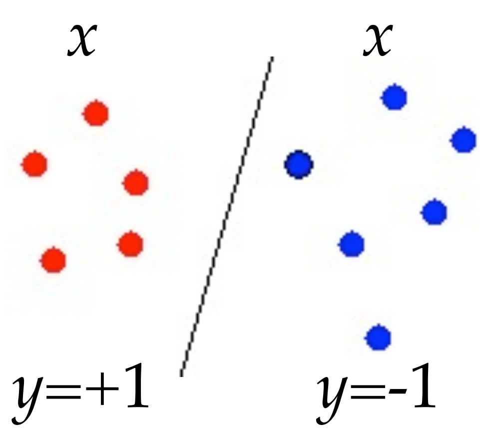

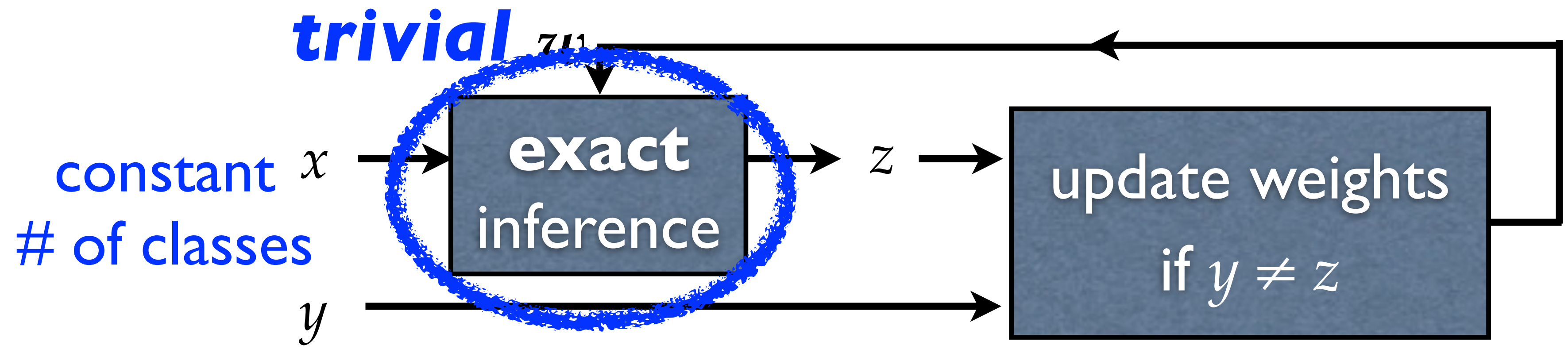

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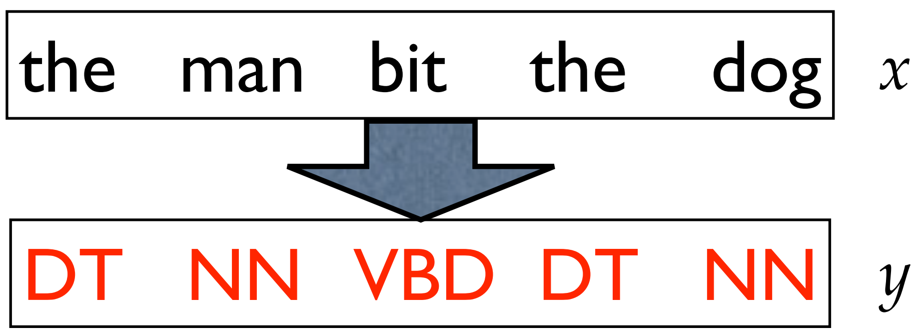
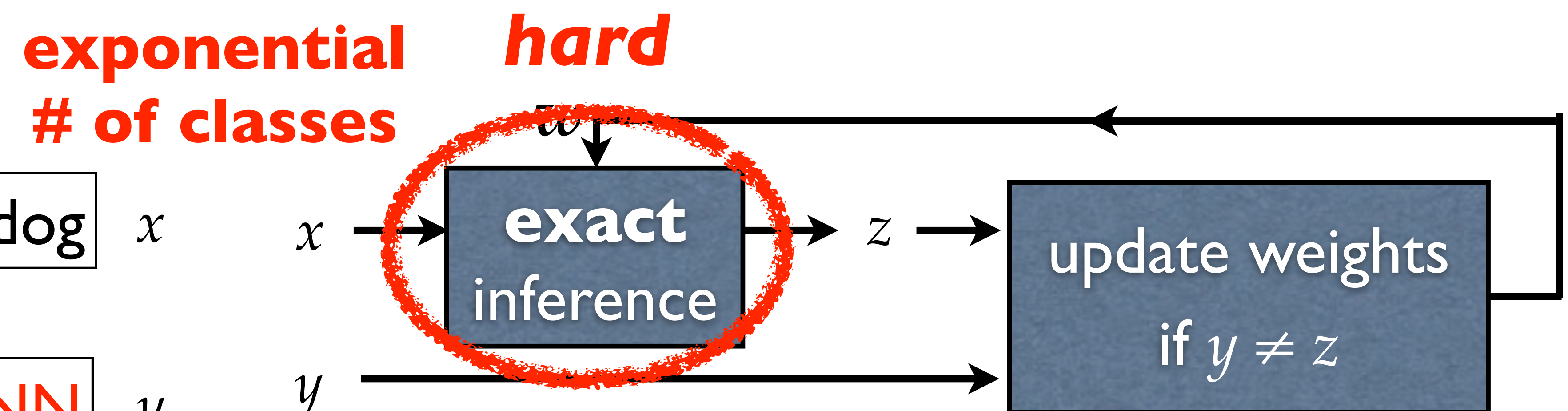
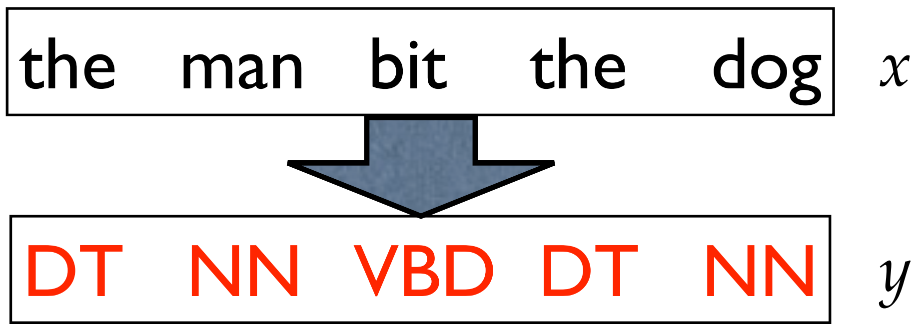
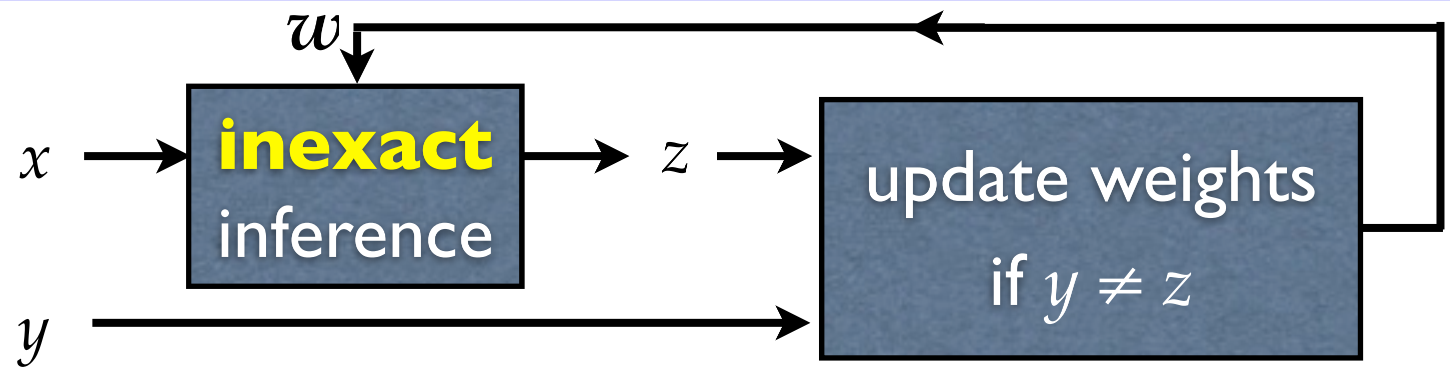


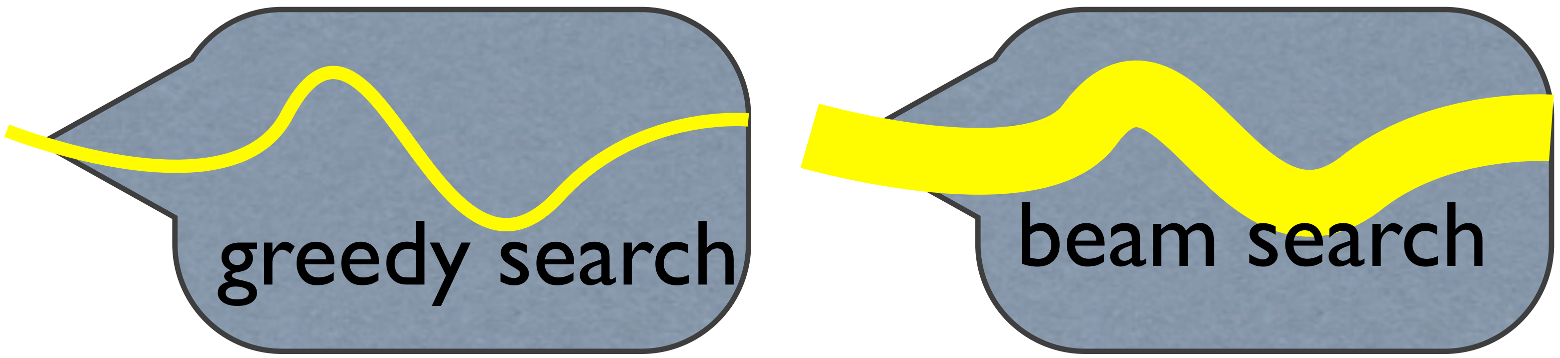


- challenge: search efficiency (exponentially many classes)
  - often use dynamic programming (DP)
  - but still too slow for repeated use, e.g. parsing is $O(n^3)$
  - and can't use non-local features in DP

Perceptron w/ Inexact Inference







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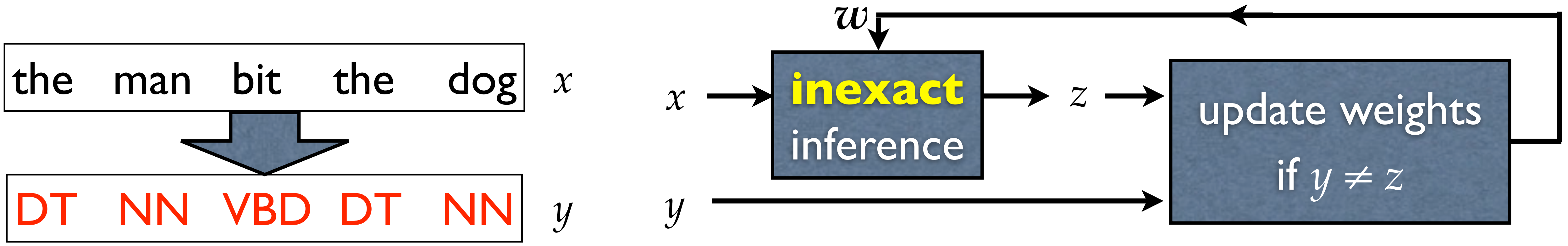

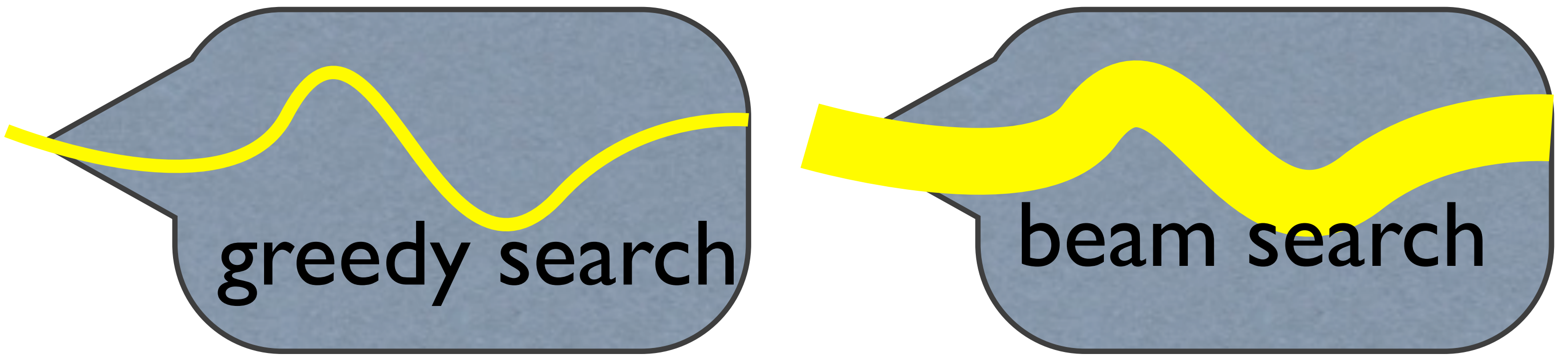

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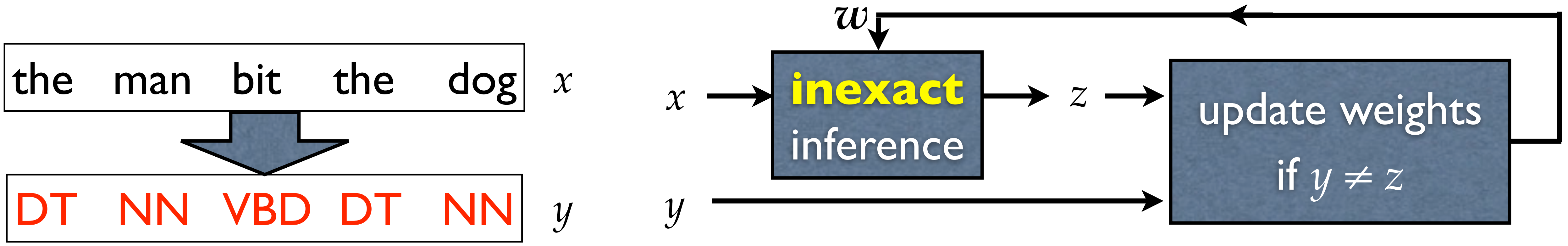

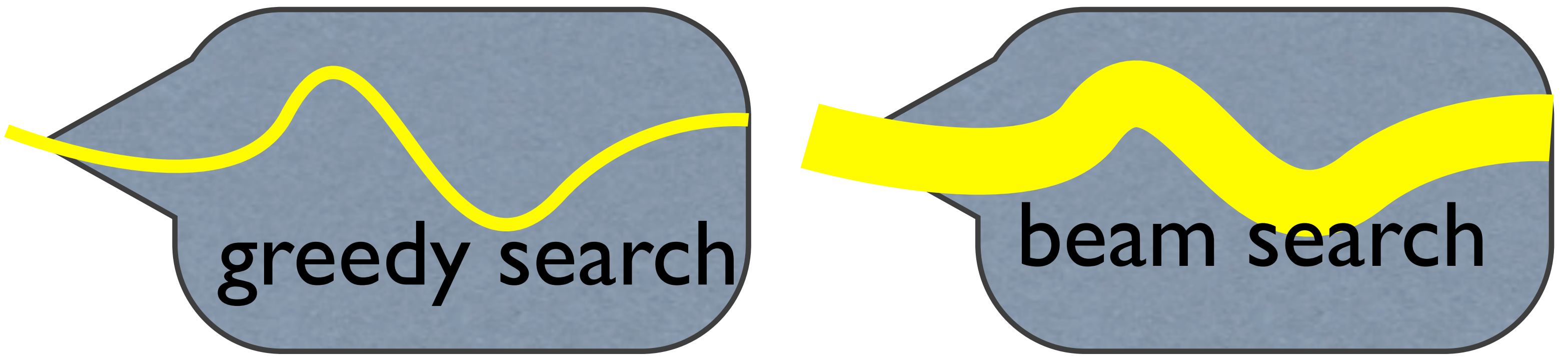

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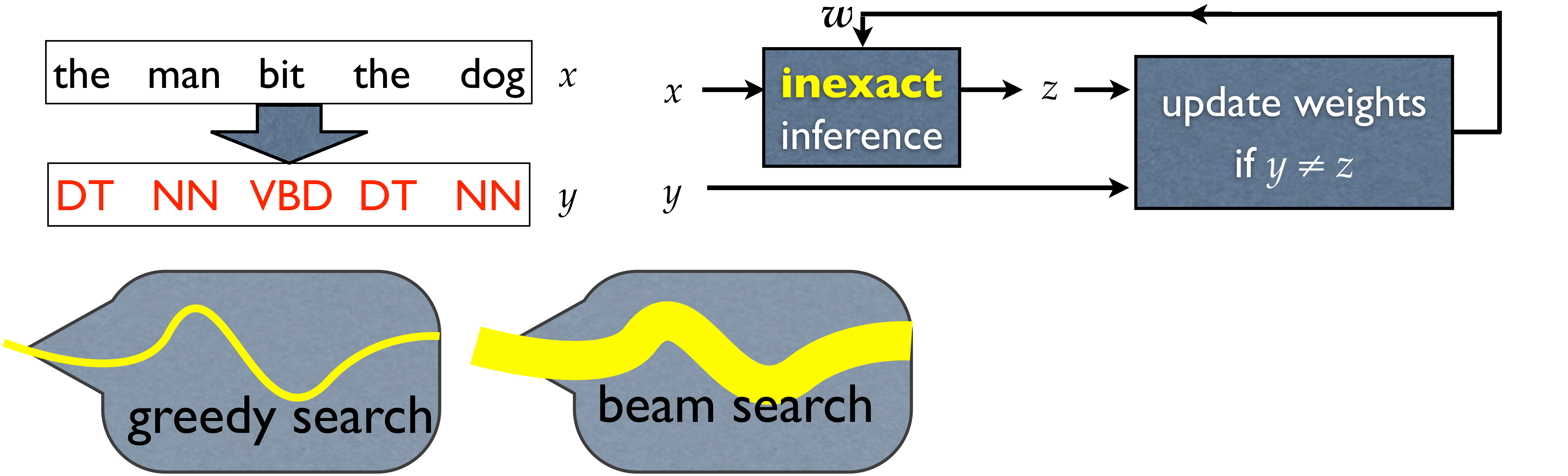

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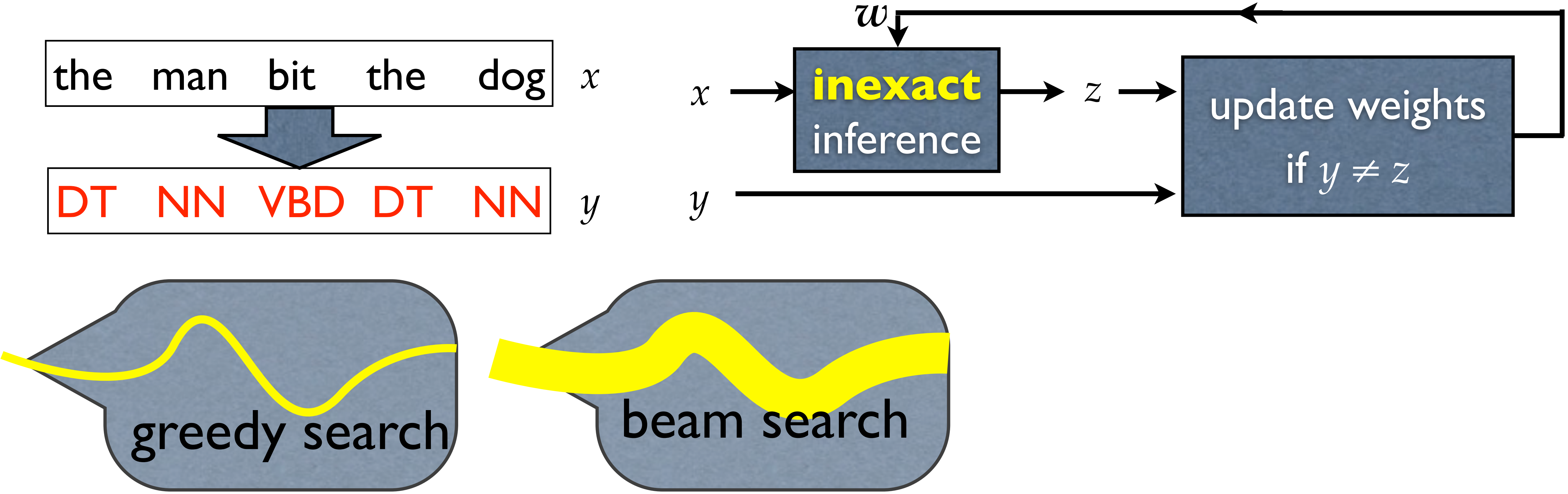

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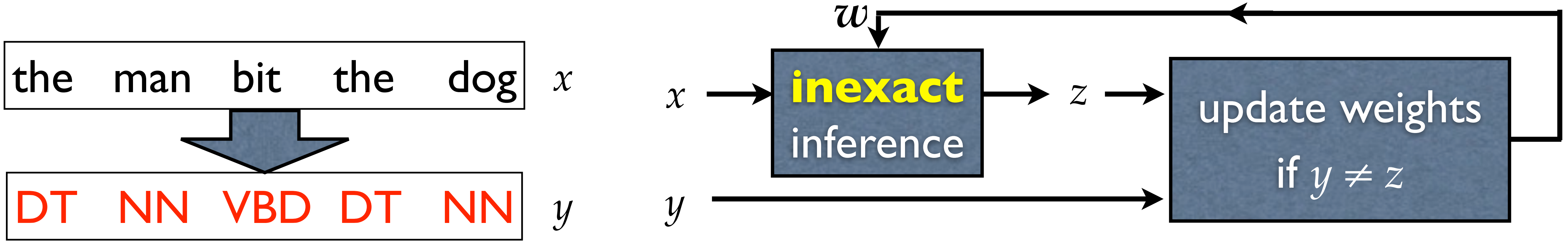
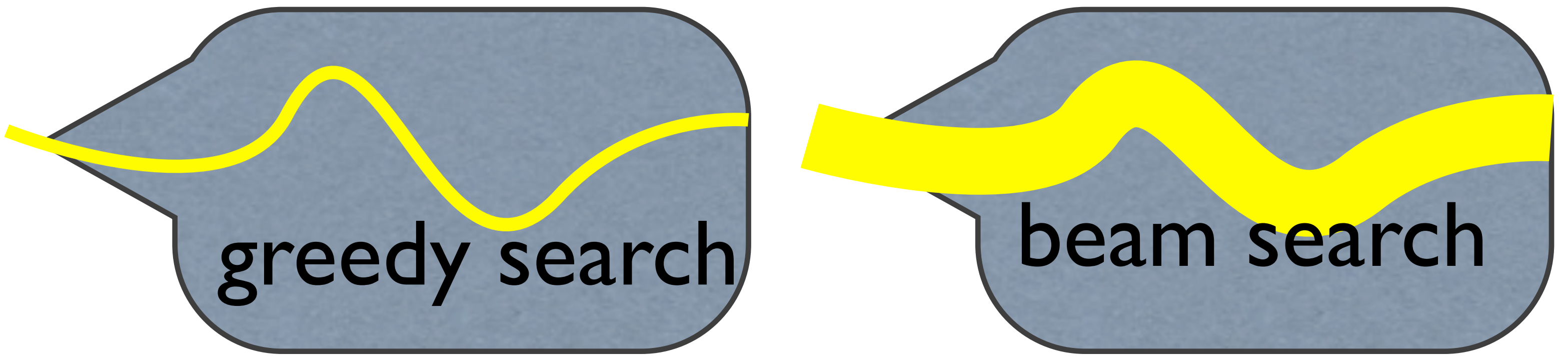
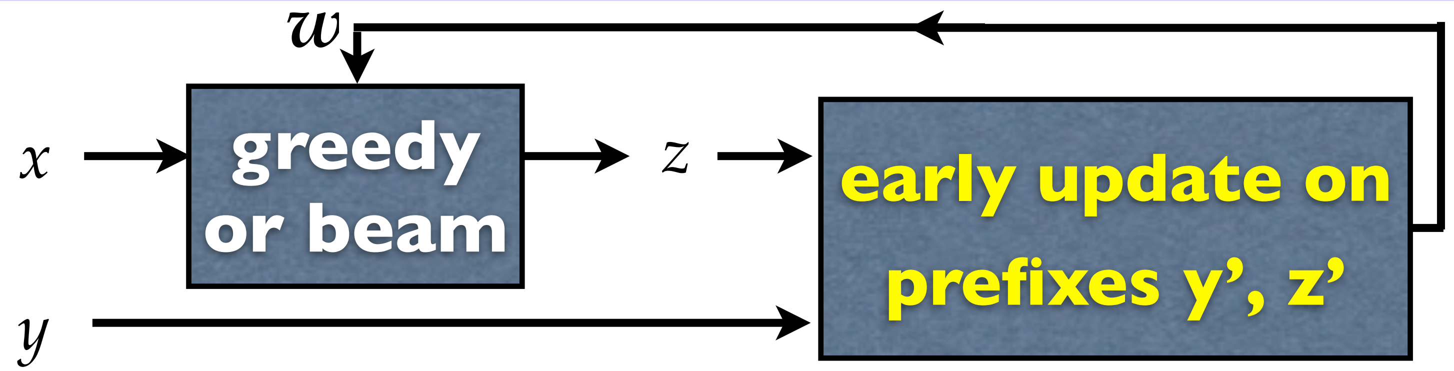




does it still work???

- routine use of inexact inference in NLP (e.g. beam search)
- how does structured perceptron work with inexact search?
  - so far most structured learning theory assume exact search
  - would search errors break these learning properties?
  - if so how to modify learning to accommodate inexact search?

Prior work: Early update (Collins/Roark)



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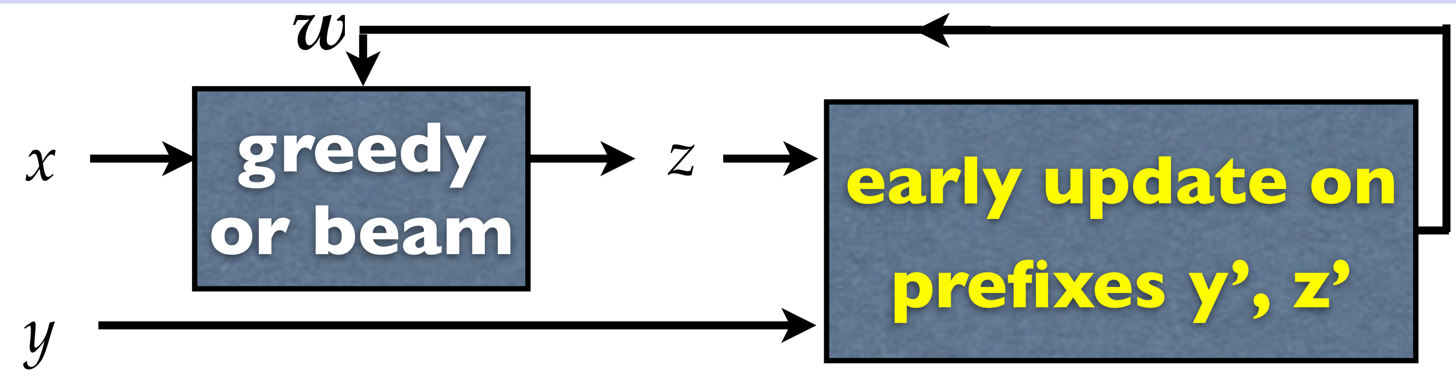

- a partial answer: "early update" (Collins & Roark, 2004)
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  - updates on prefixes rather than full sequences
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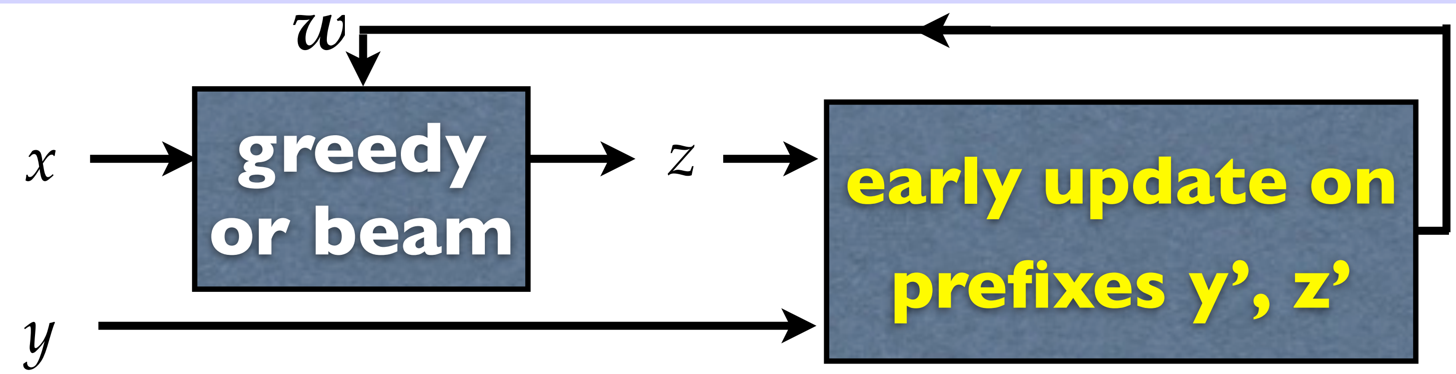

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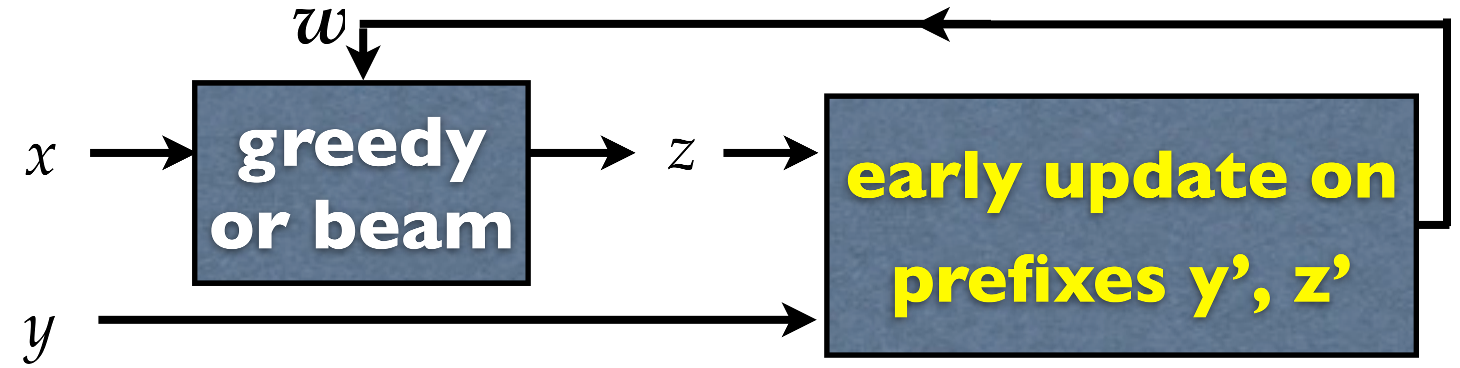

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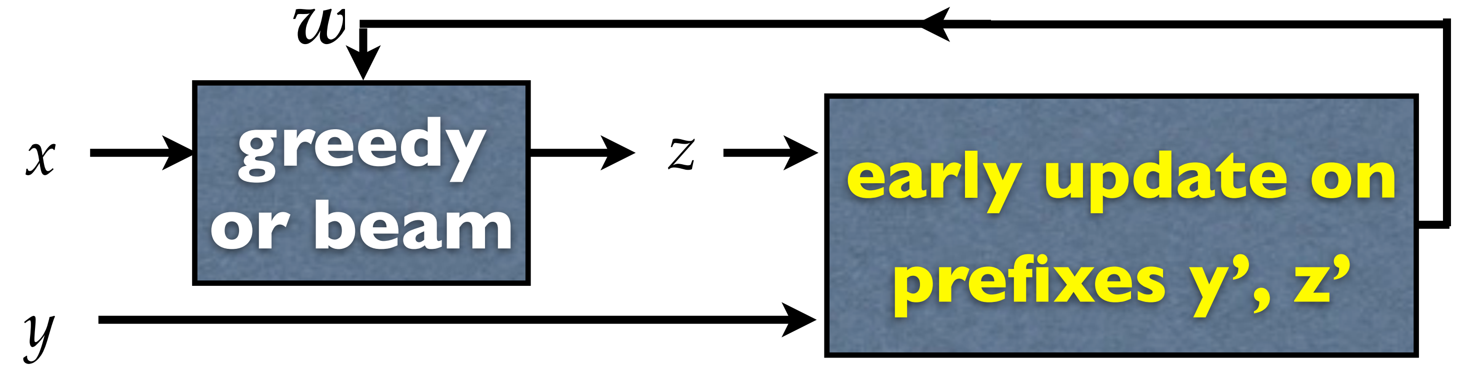
- two major problems for early update
  - there is no theoretical justification -- why does it work?
  - it learns too slowly (due to partial examples); e.g. 40 epochs
- we'll solve problems in a much larger framework

Our Contributions



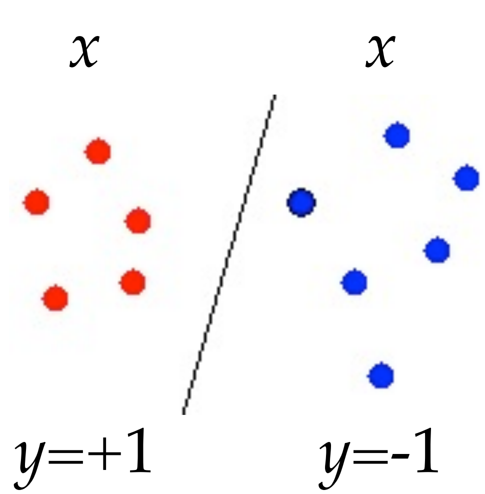
- theory: a framework for perceptron w/ inexact search
  - explains early update (and others) as a special case
- practice: new update methods within the framework
  - converges faster and better than early update
  - real impact on state-of-the-art parsing and tagging
  - more advantageous when search error is severer

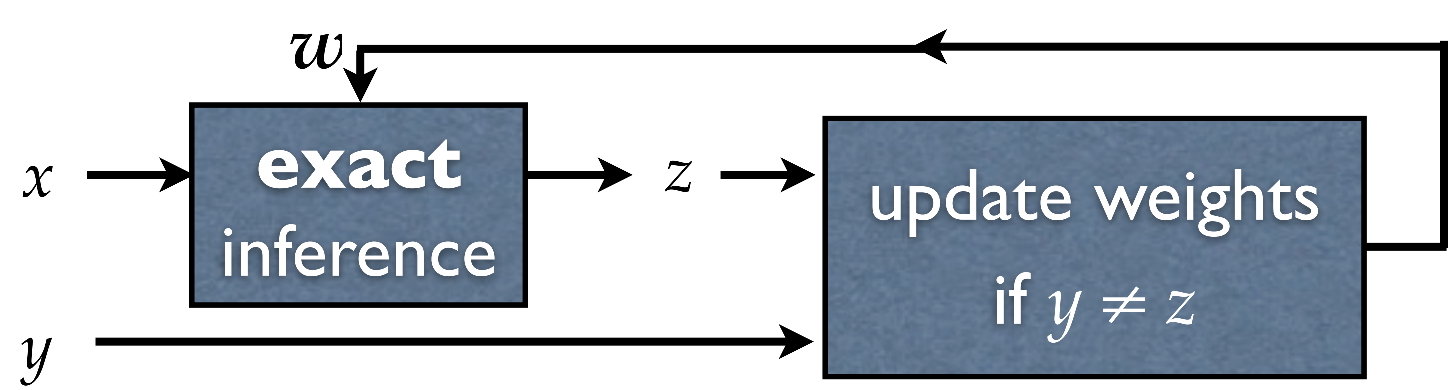
In this talk...

- Motivations: Structured Learning and Search Efficiency
- Structured Perceptron and Inexact Search
  - perceptron does not converge with inexact search
  - early update (Collins/Roark '04) seems to help; but why?
- New Perceptron Framework for Inexact Search
  - explains early update as a special case
  - convergence theory with *arbitrarily* inexact search
  - new update methods within this framework
- Experiments

Structured Perceptron (Collins 02)

- simple generalization from binary/multiclass perceptron
- online learning: for each example (x, y) in data
  - inference: find the best output z given current weight w
  - update weights when if y ≠ z





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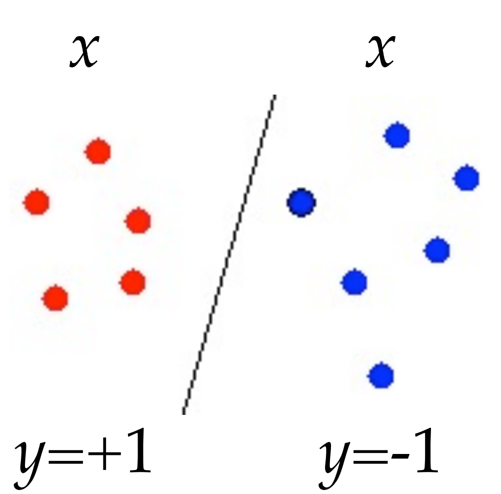

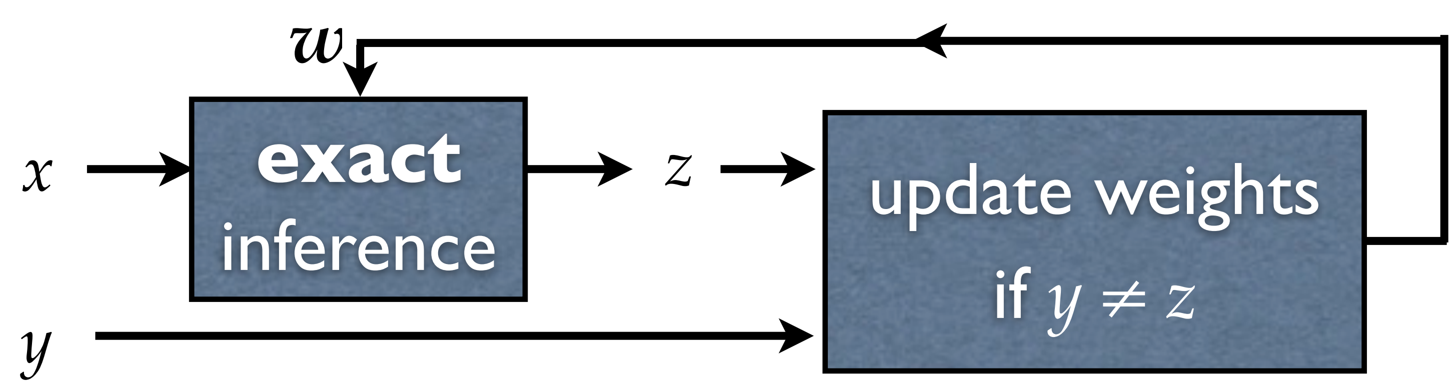

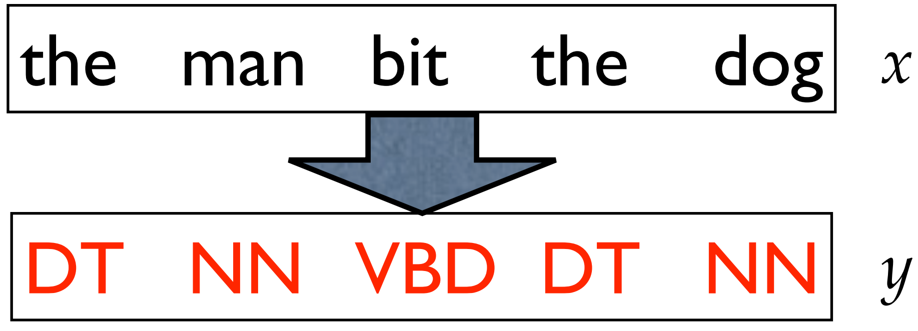

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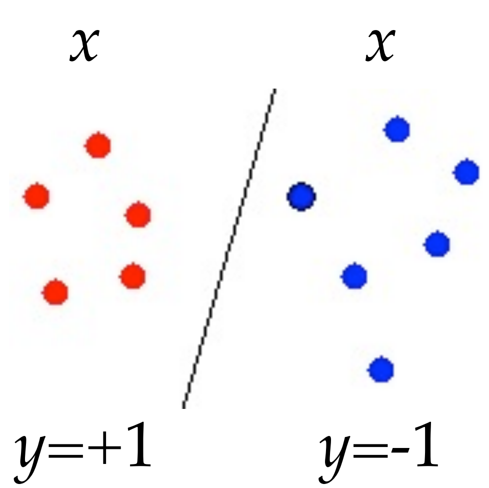

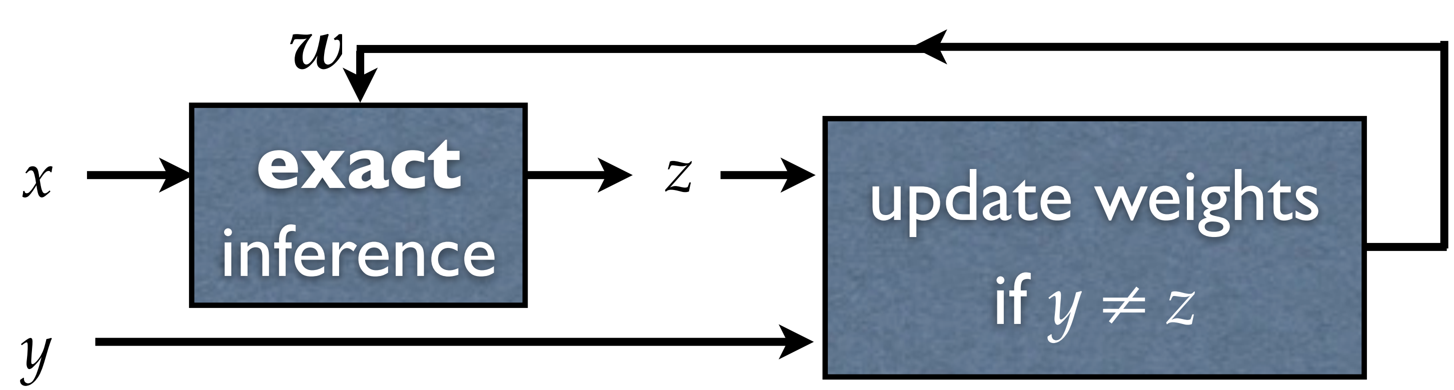

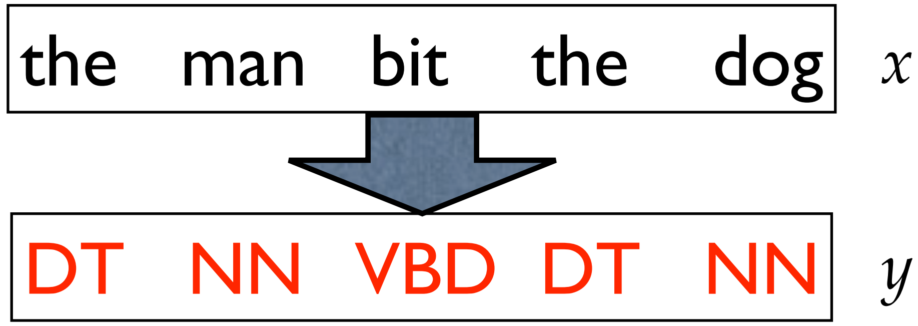

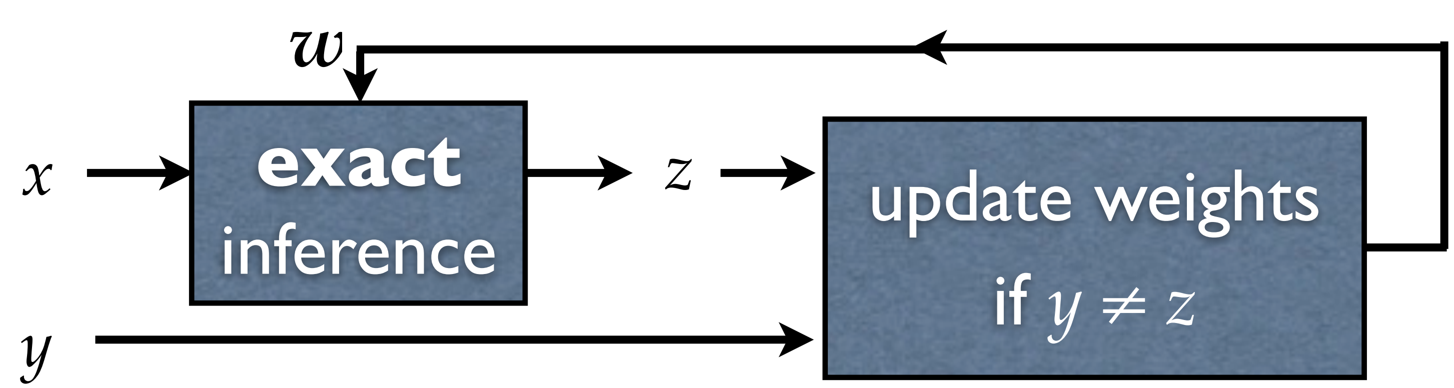

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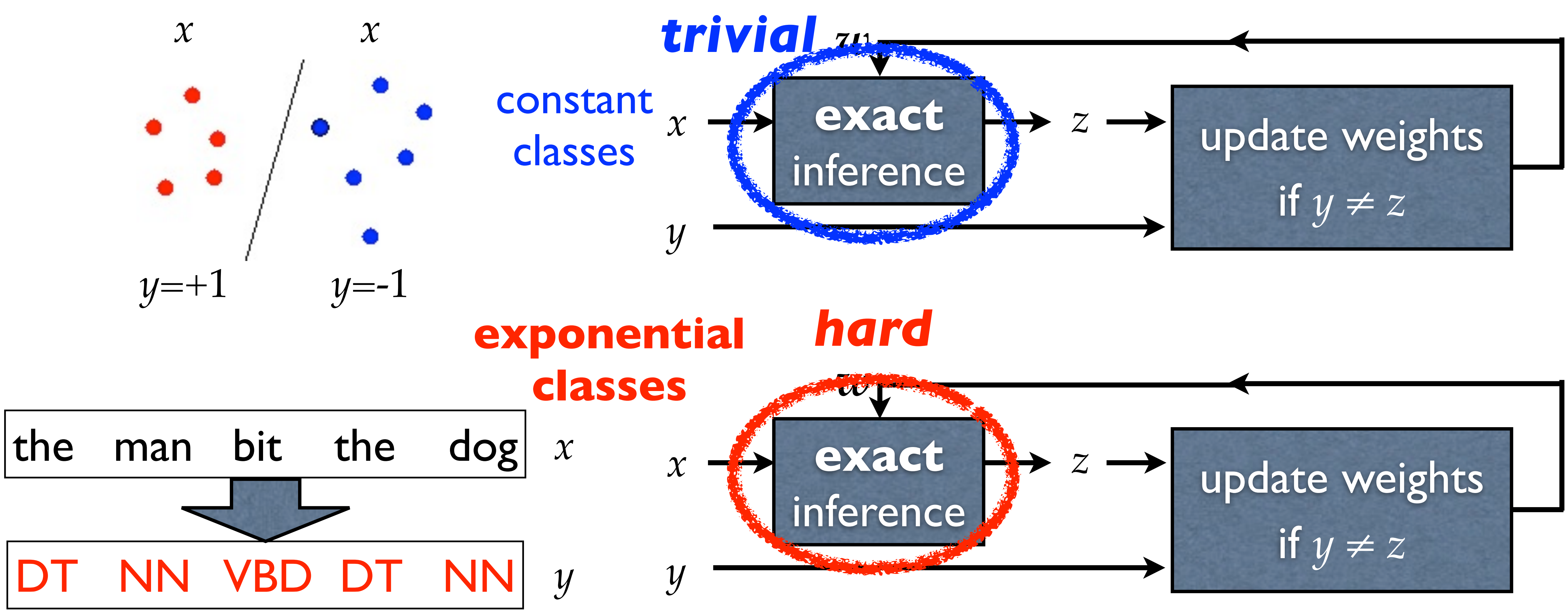
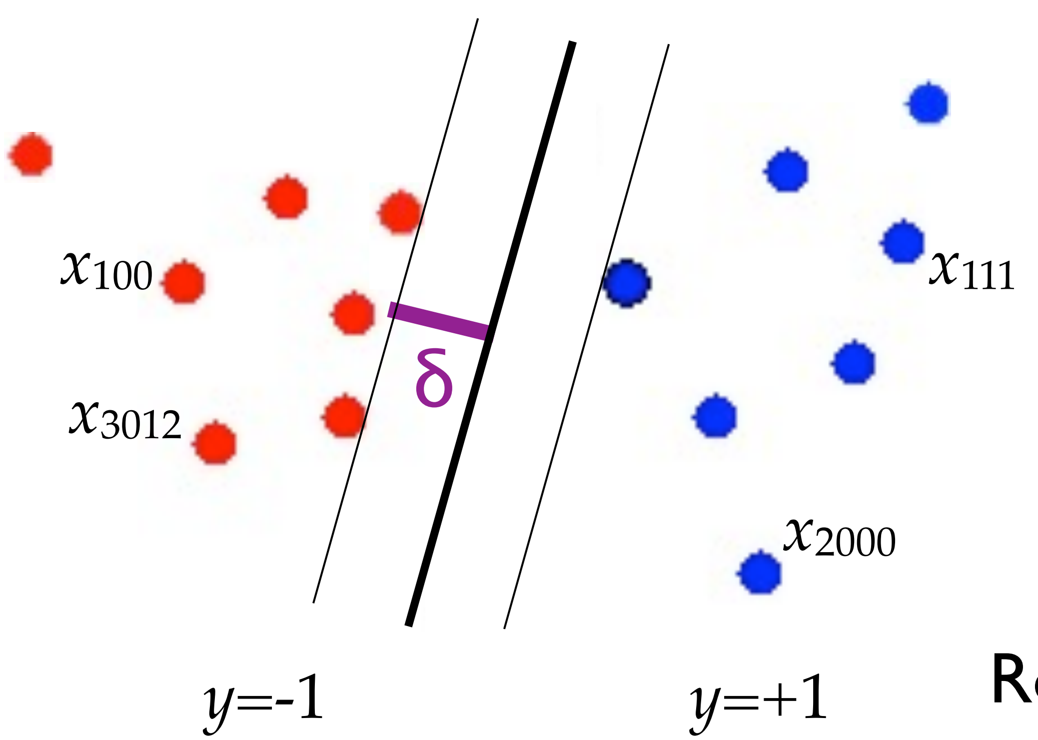
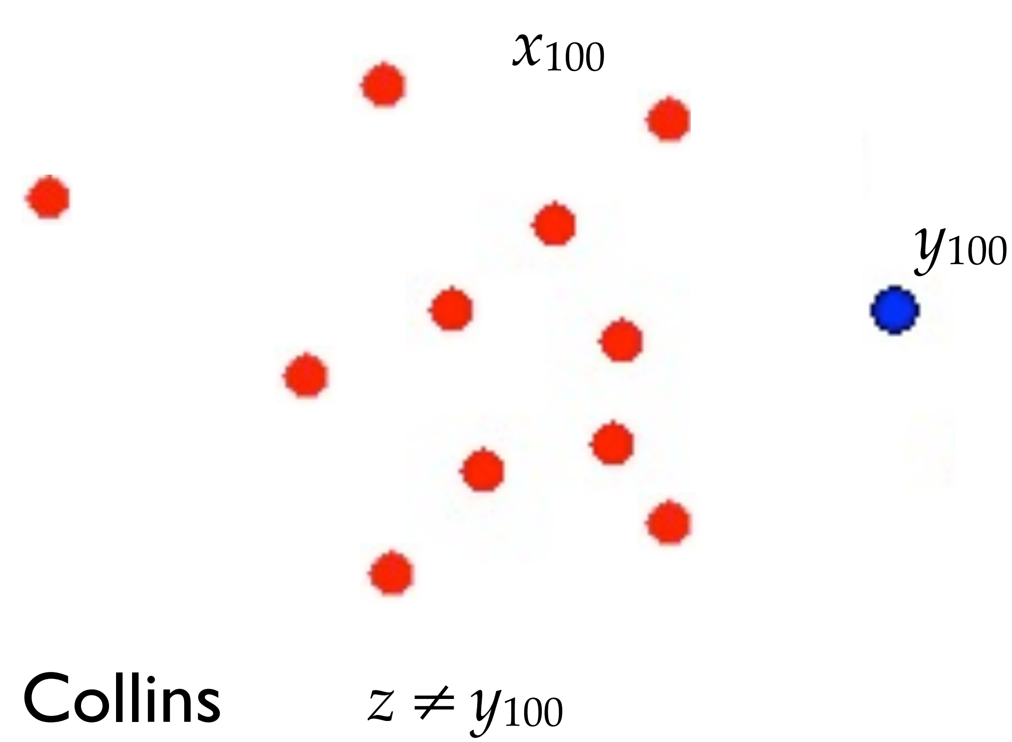


Convergence with Exact Search

- linear classification: converges iff. data is separable
- structured: converges iff. data separable & search exact
  - there is an oracle vector that correctly labels all examples
  - one vs the rest (correct label better than all incorrect labels)
- theorem: if separable, then **# of updates ≤ R^2 / δ^2**   R: diameter



Rosenblatt => Collins
1957 2002



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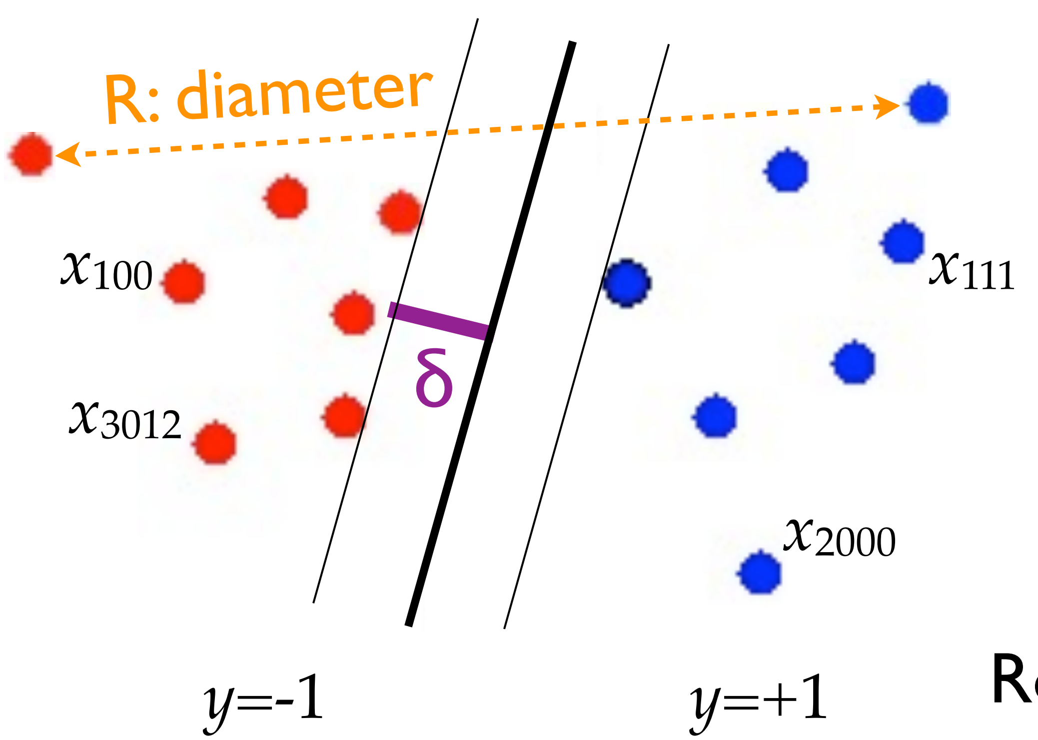

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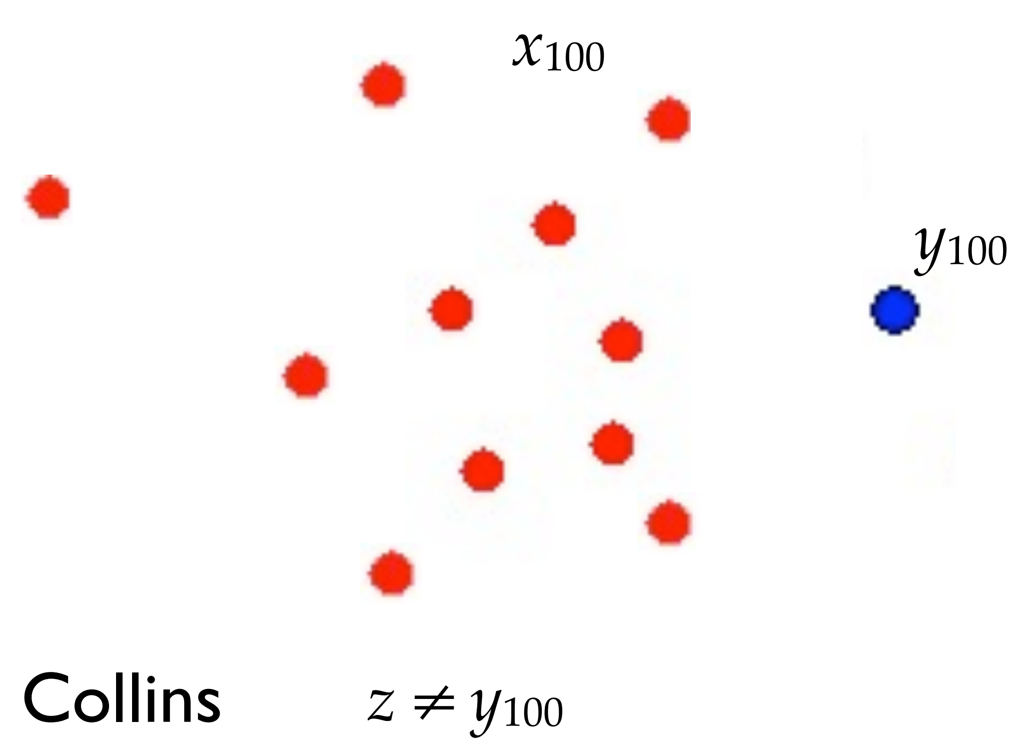

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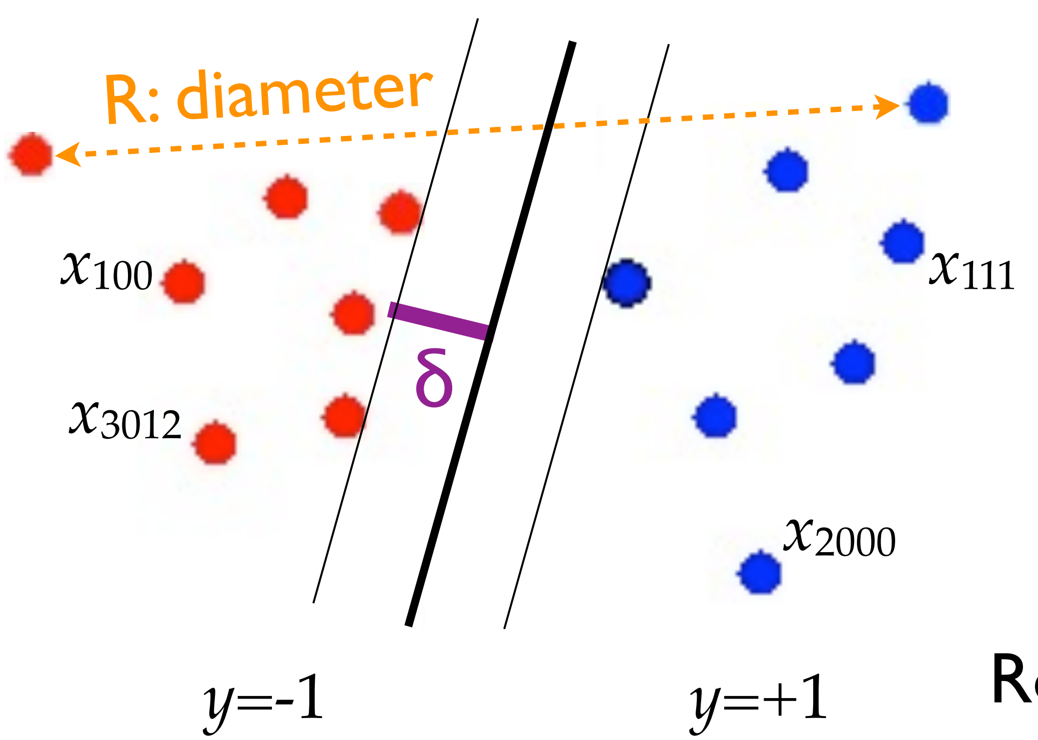

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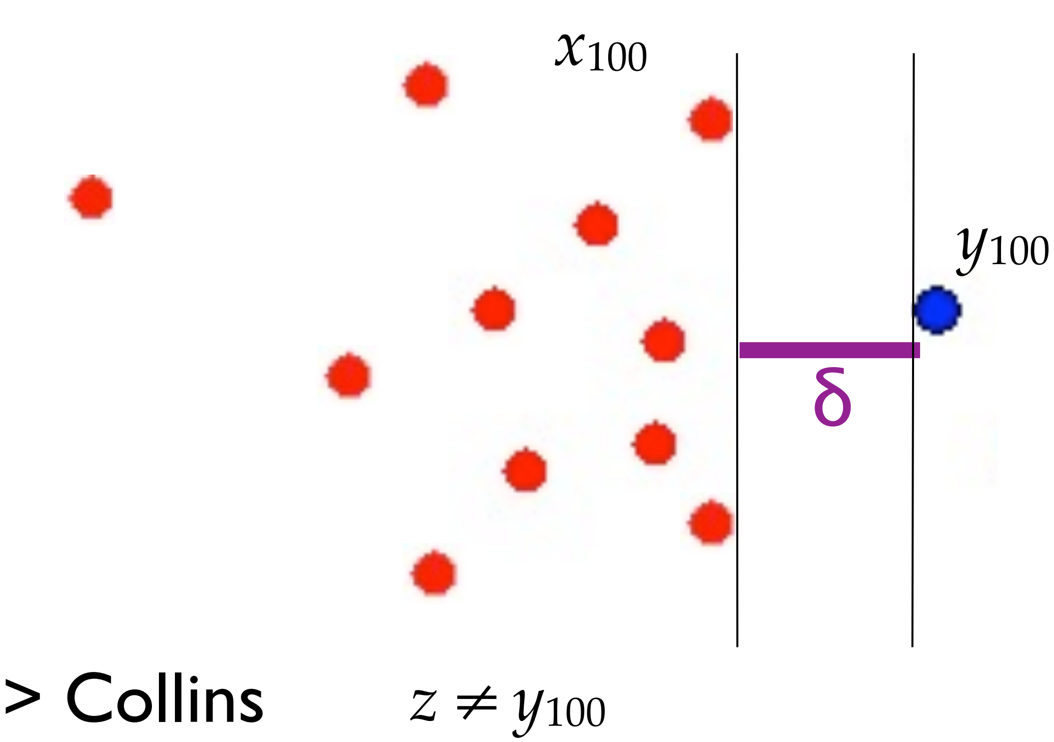

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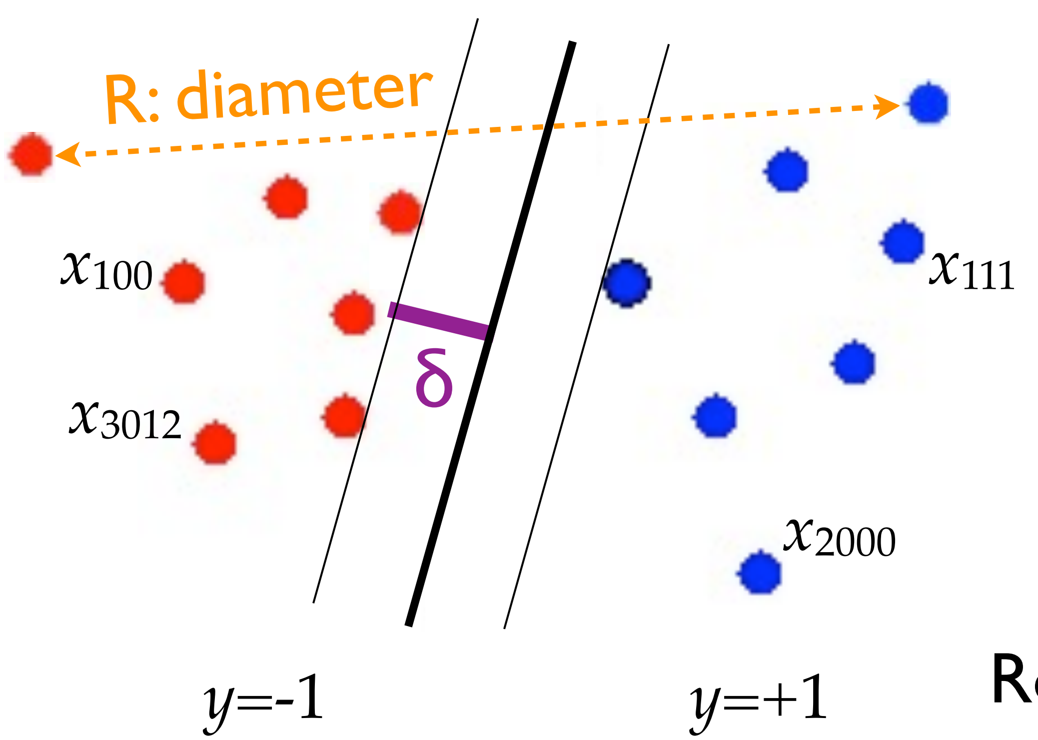

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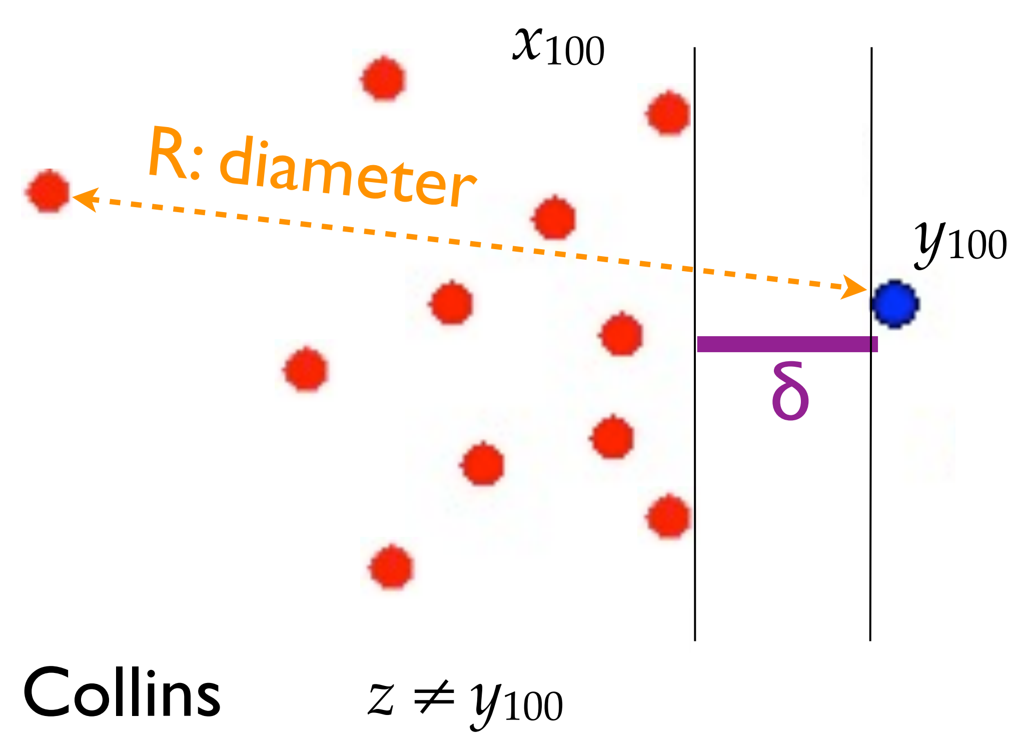
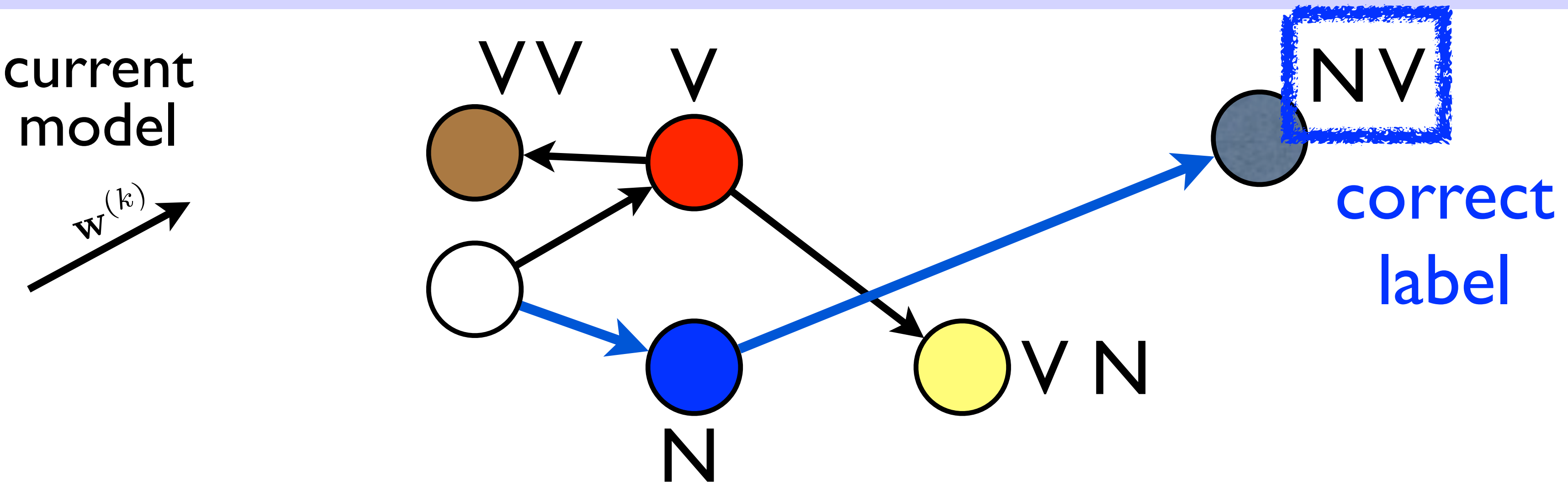


No Convergence w/ Greedy Search

current model



training example

time flies
N V

output space
{N,V} x {N,V}

No Convergence w/ Greedy Search

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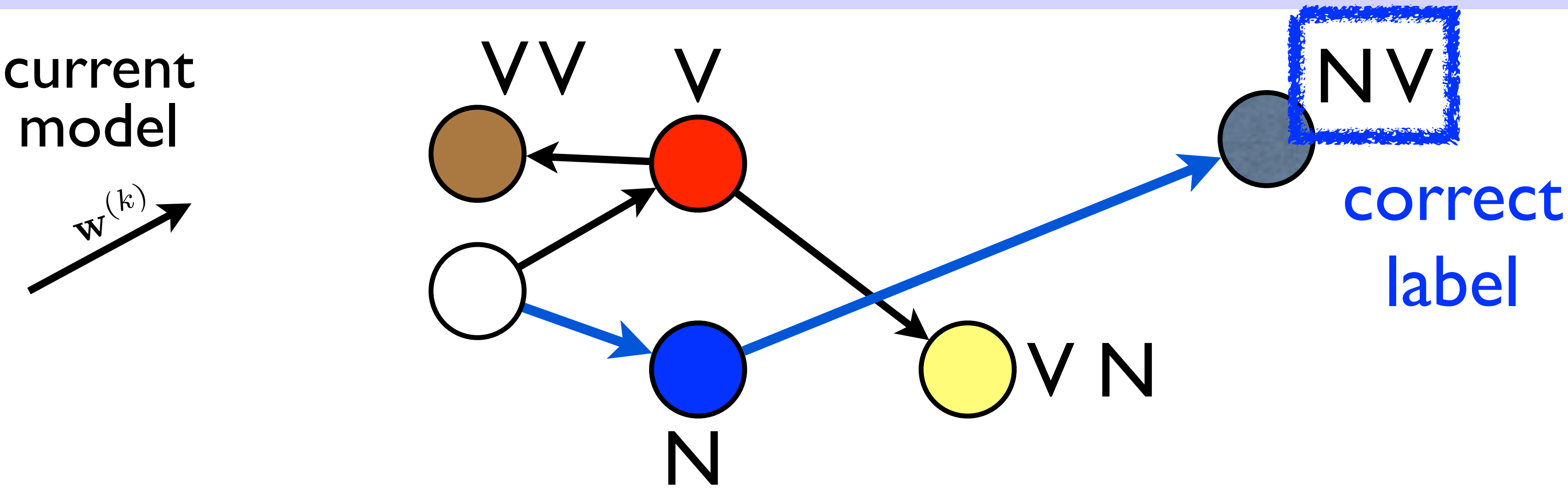

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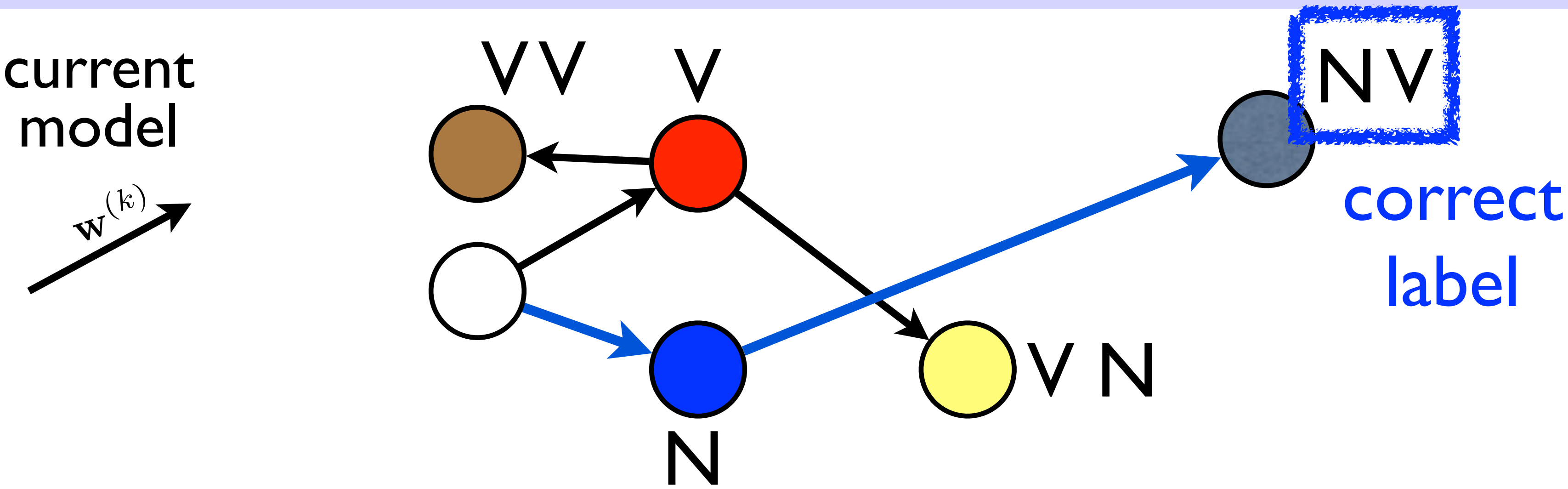

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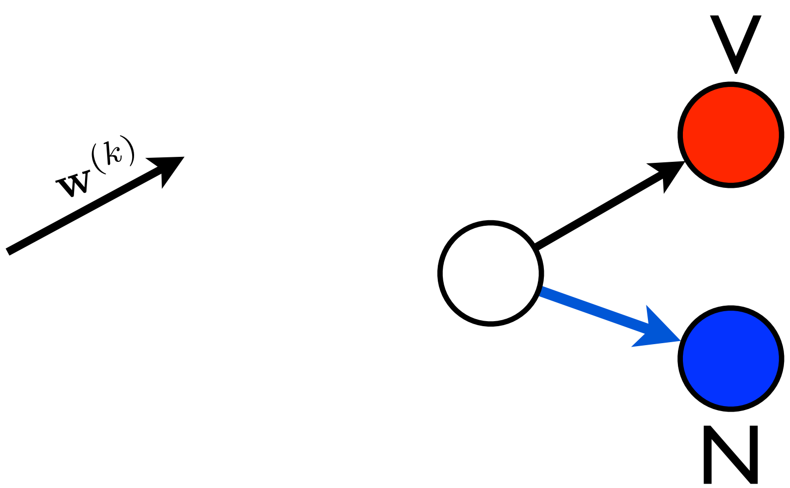

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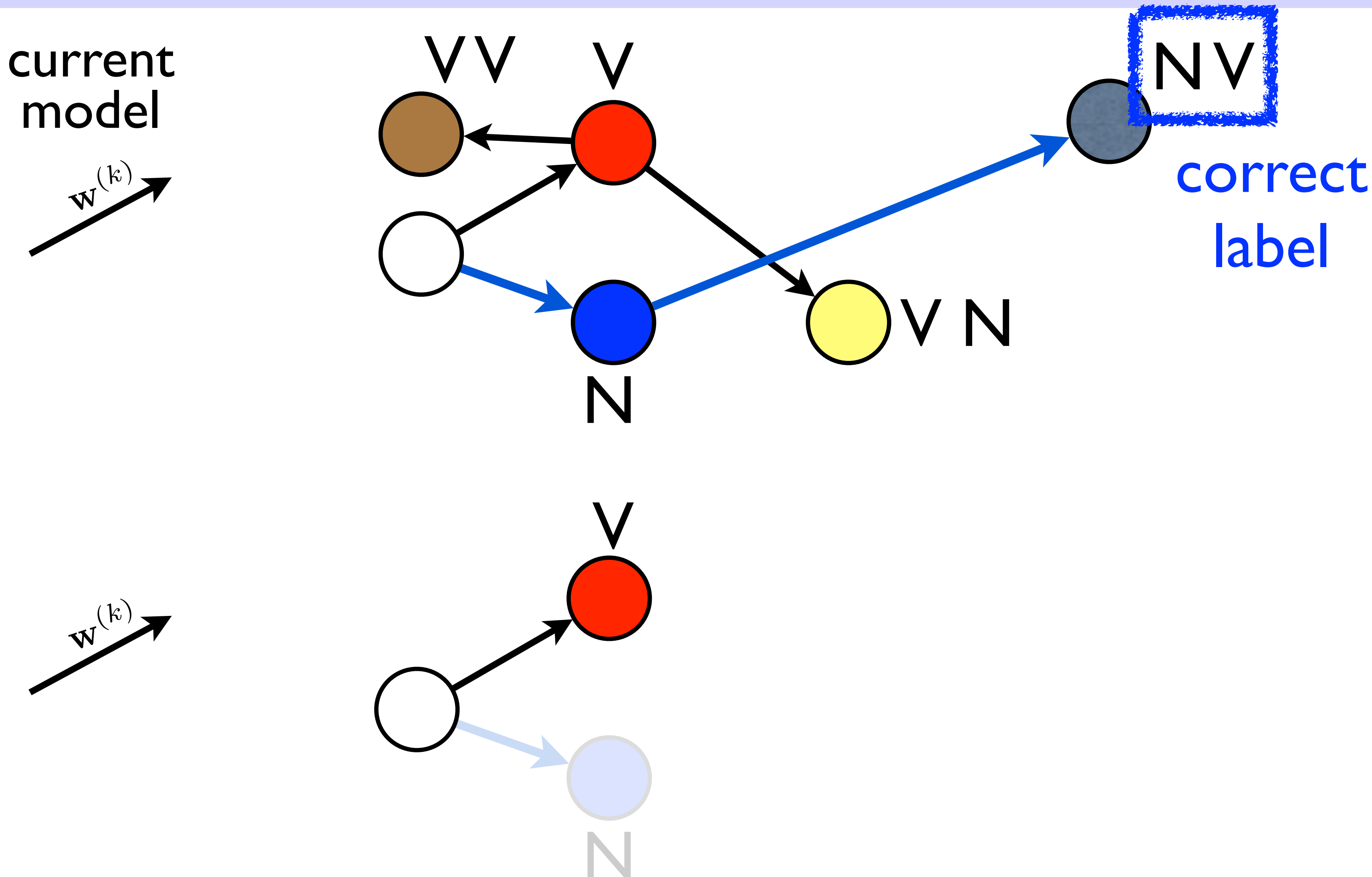

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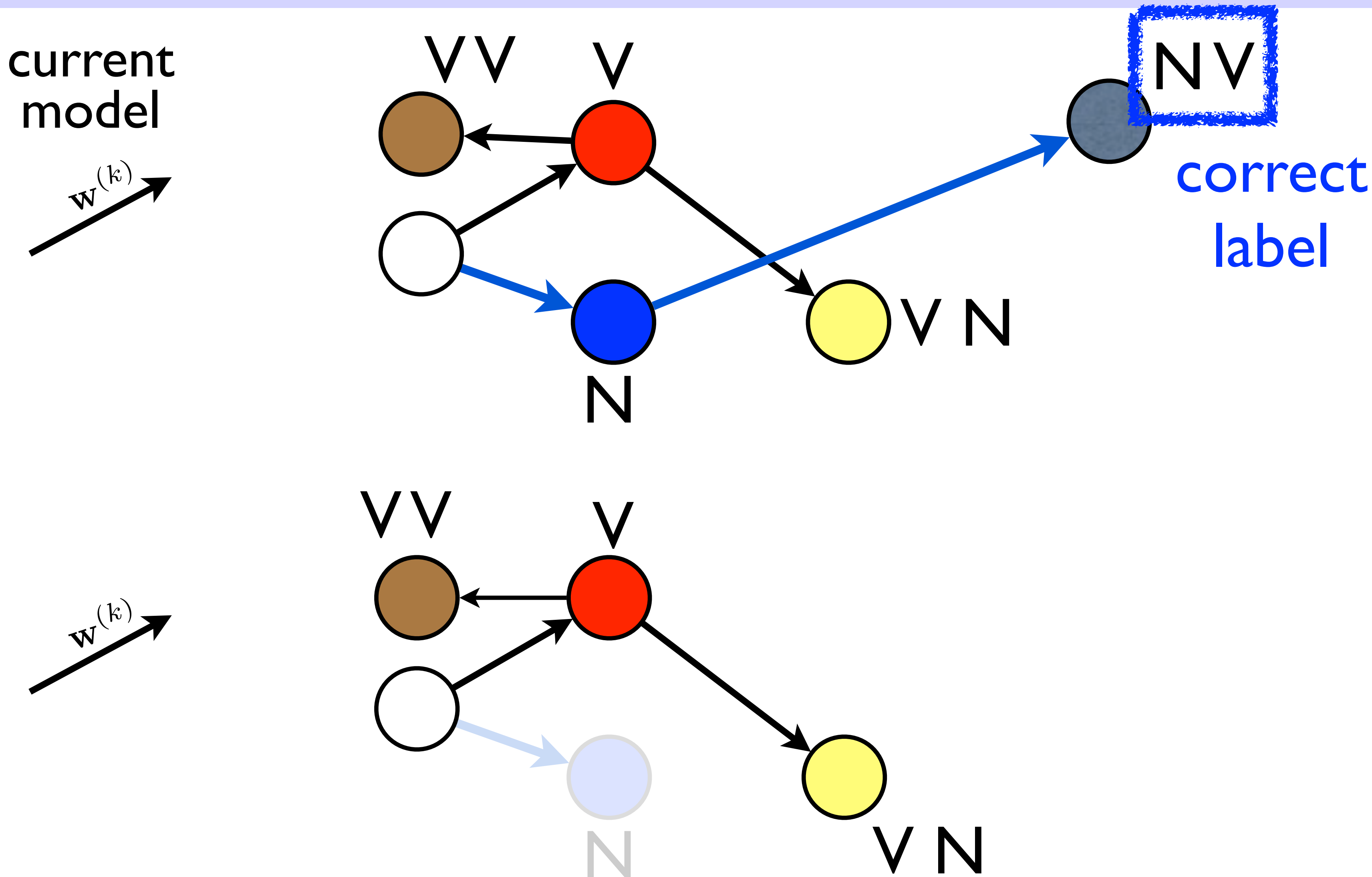

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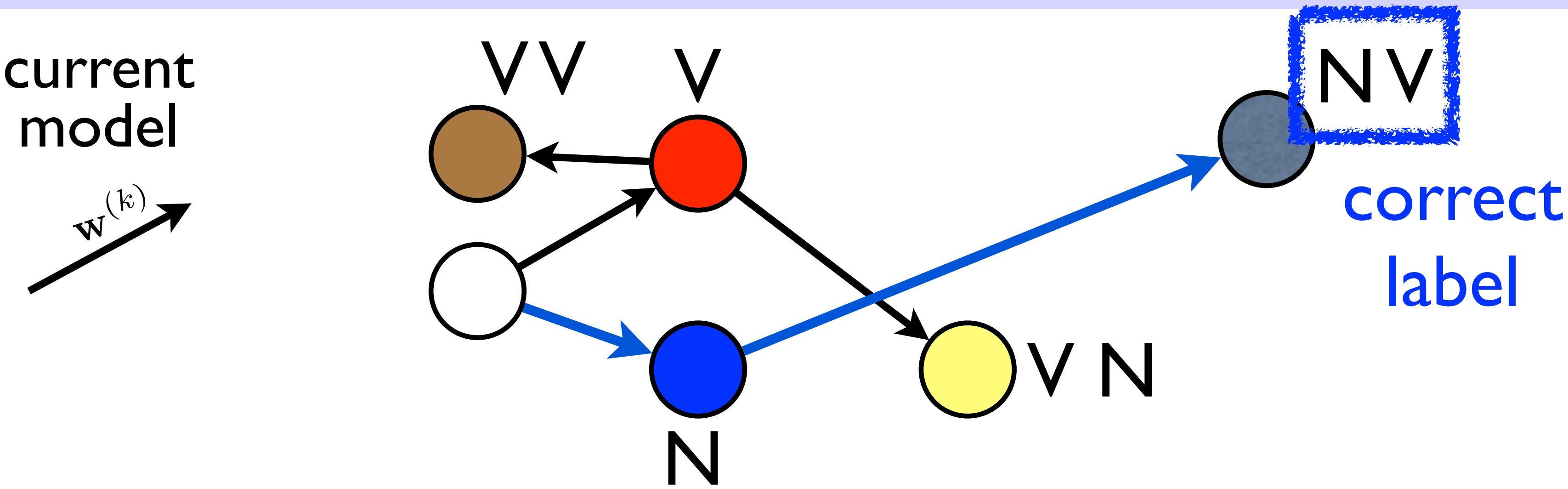

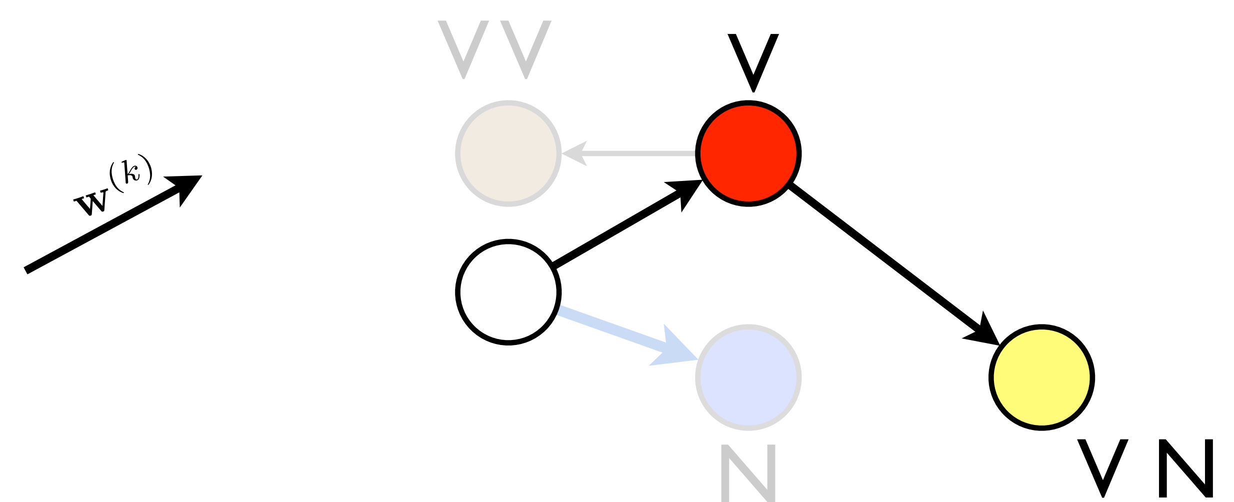

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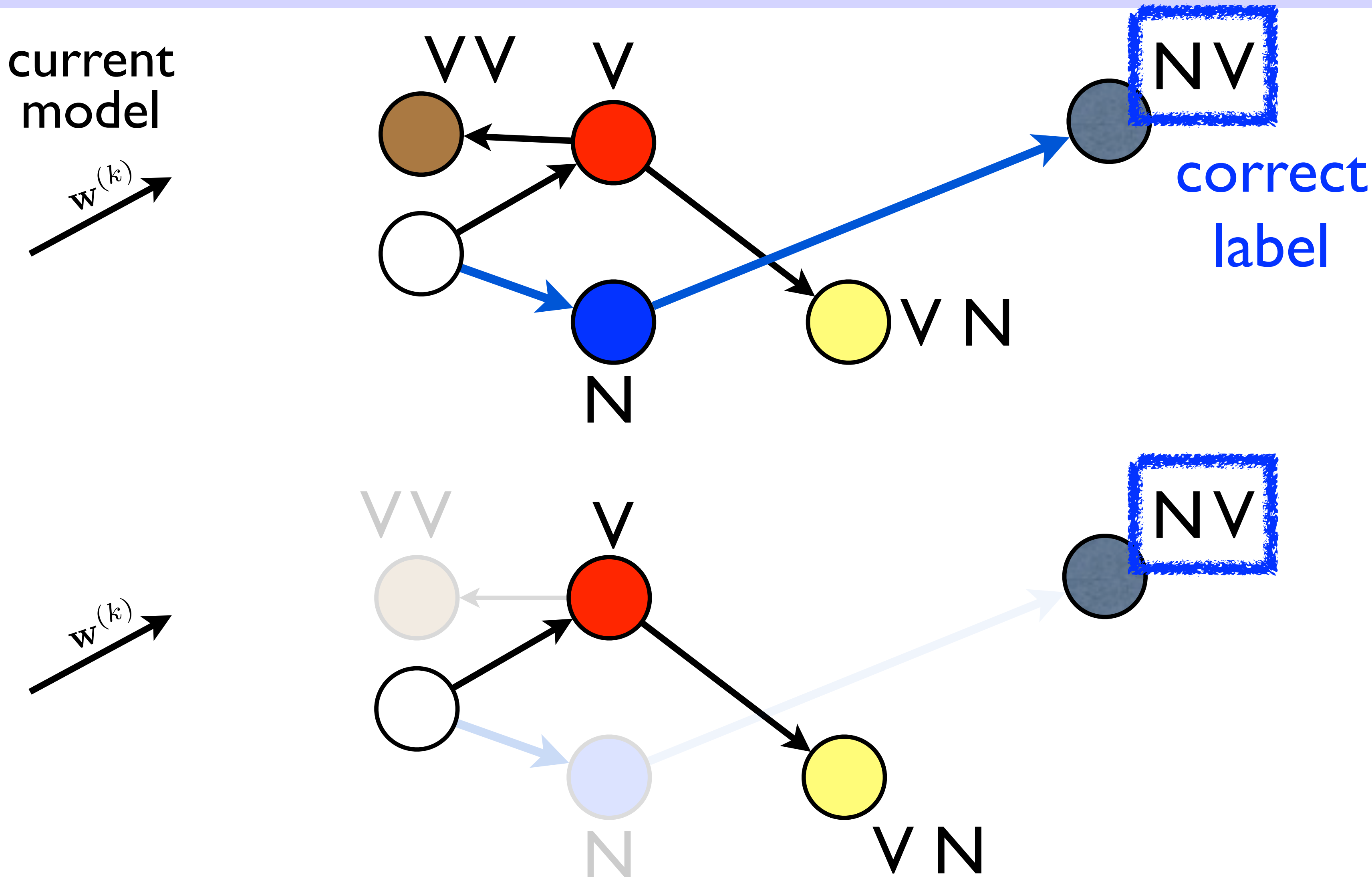

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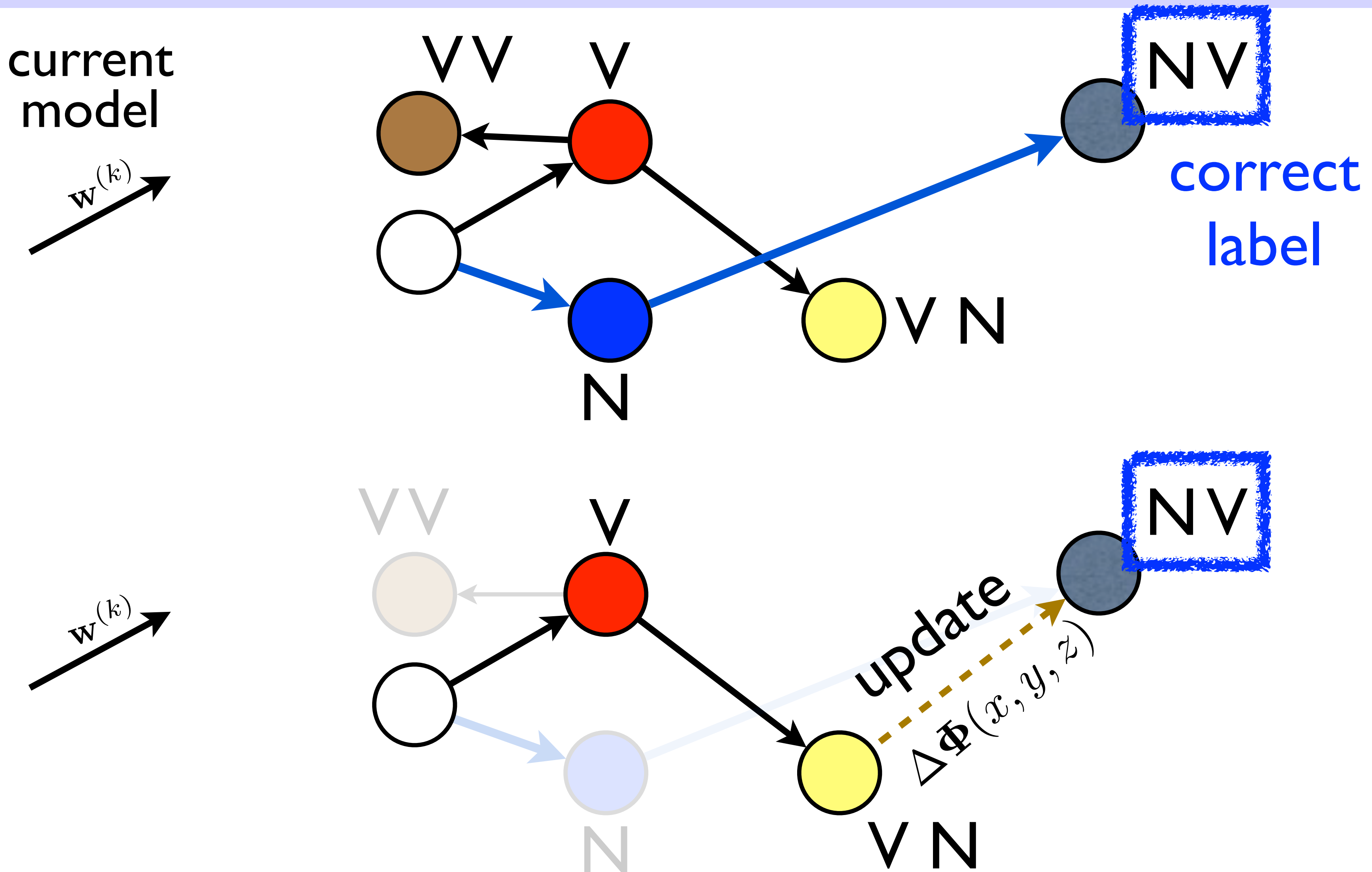
{N,V} x {N,V}

No Convergence w/ Greedy Search



training example

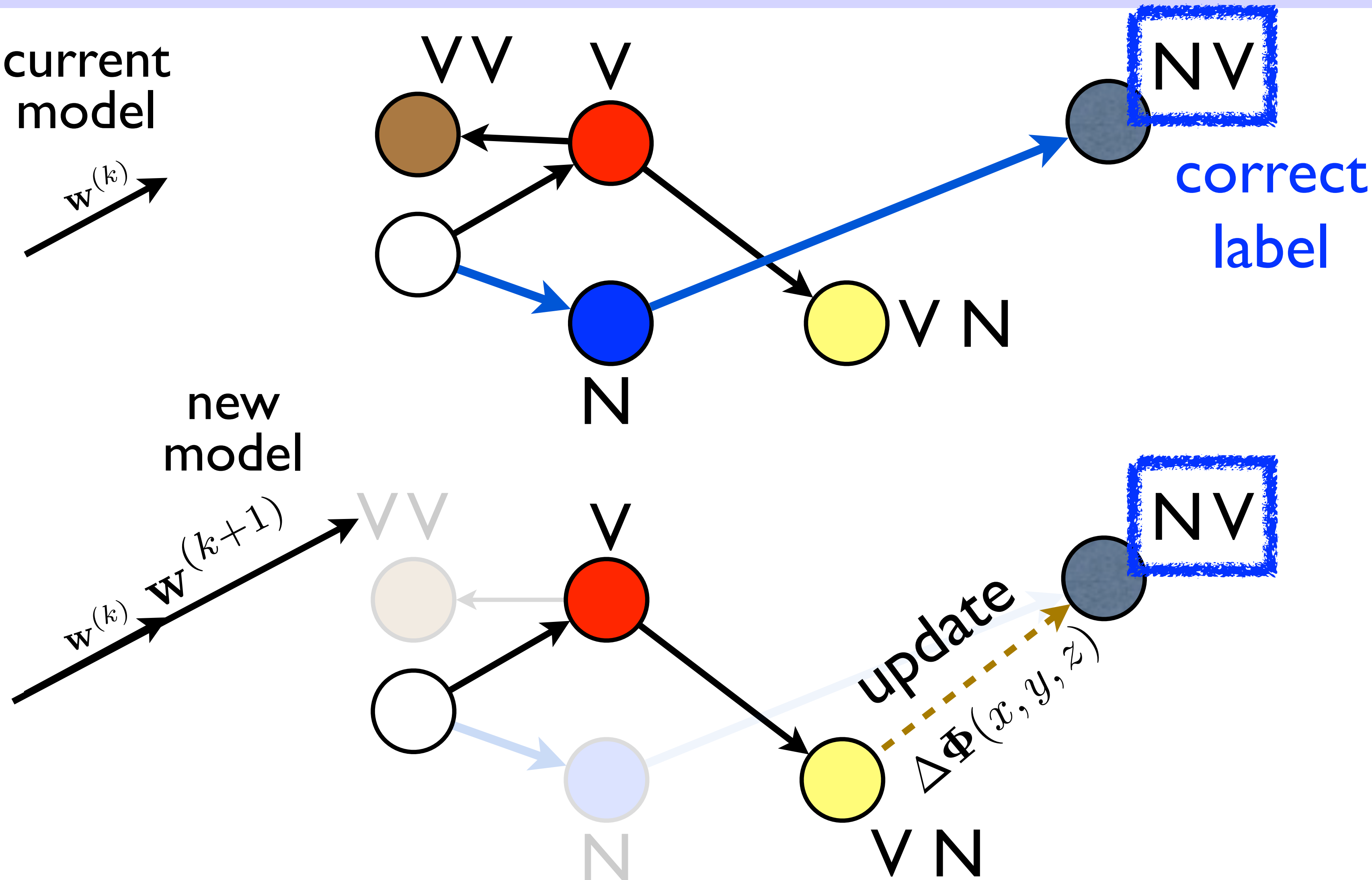
time flies

N V

output space

{N,V} x {N,V}

No Convergence w/ Greedy Search



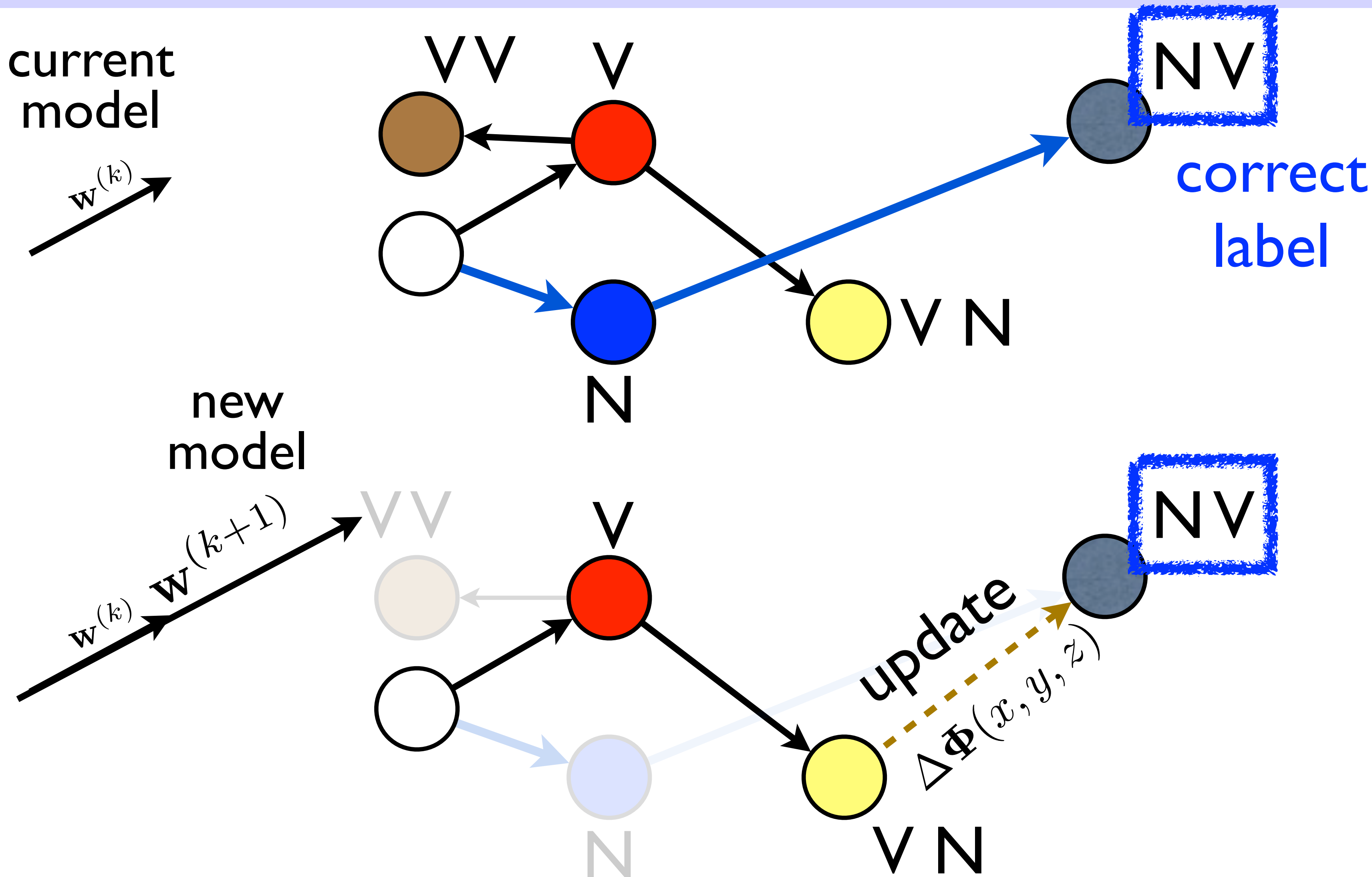
training example

time	flies
N	V

output space

{N,V} x {N,V}

No Convergence w/ Greedy Search



training example

time flies

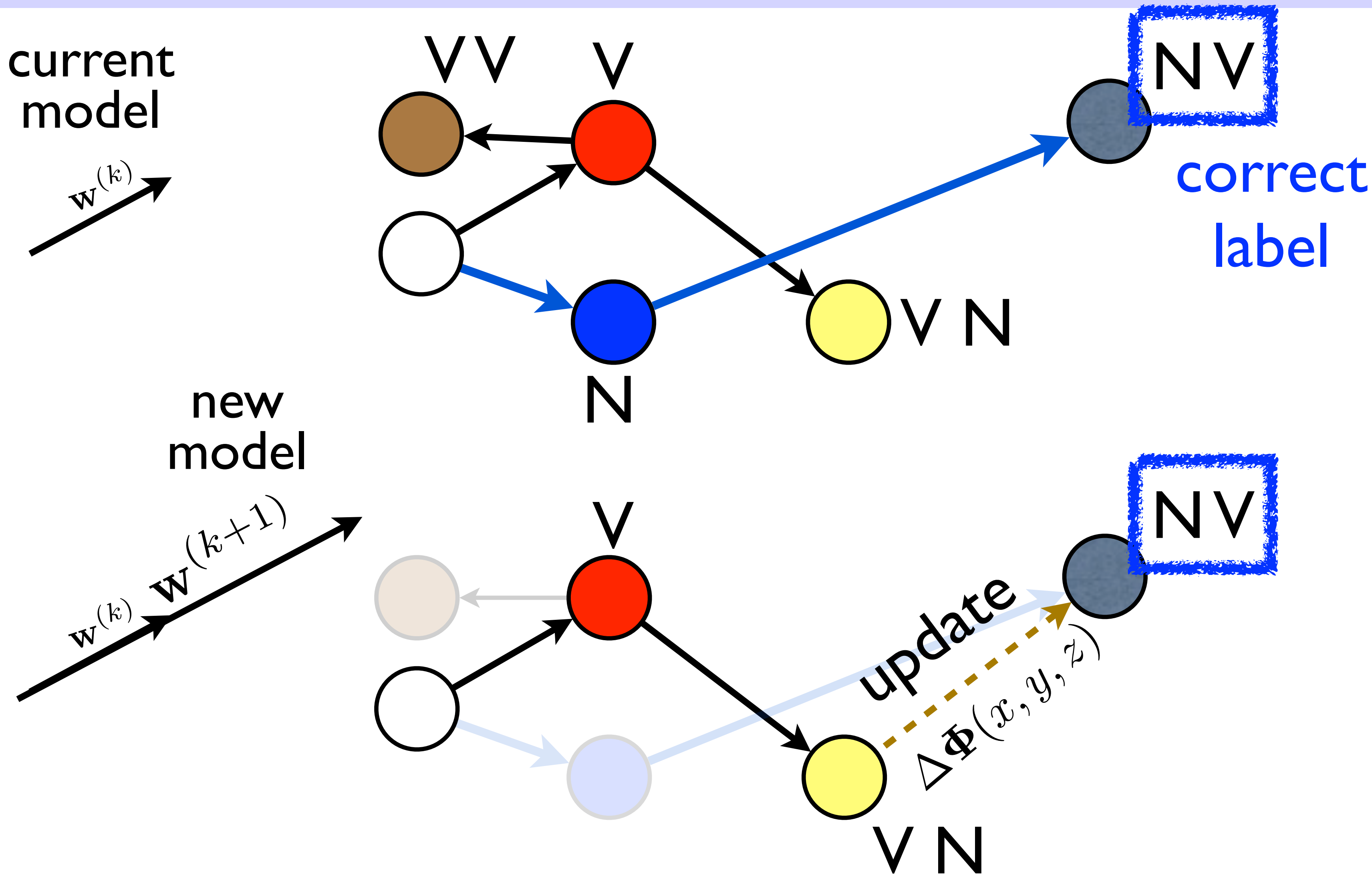
N V

output space

{N,V} x {N,V}

standard perceptron does not converge with greedy search

Early update (Collins/Roark 2004) to rescue



training example

time flies

N V

output space

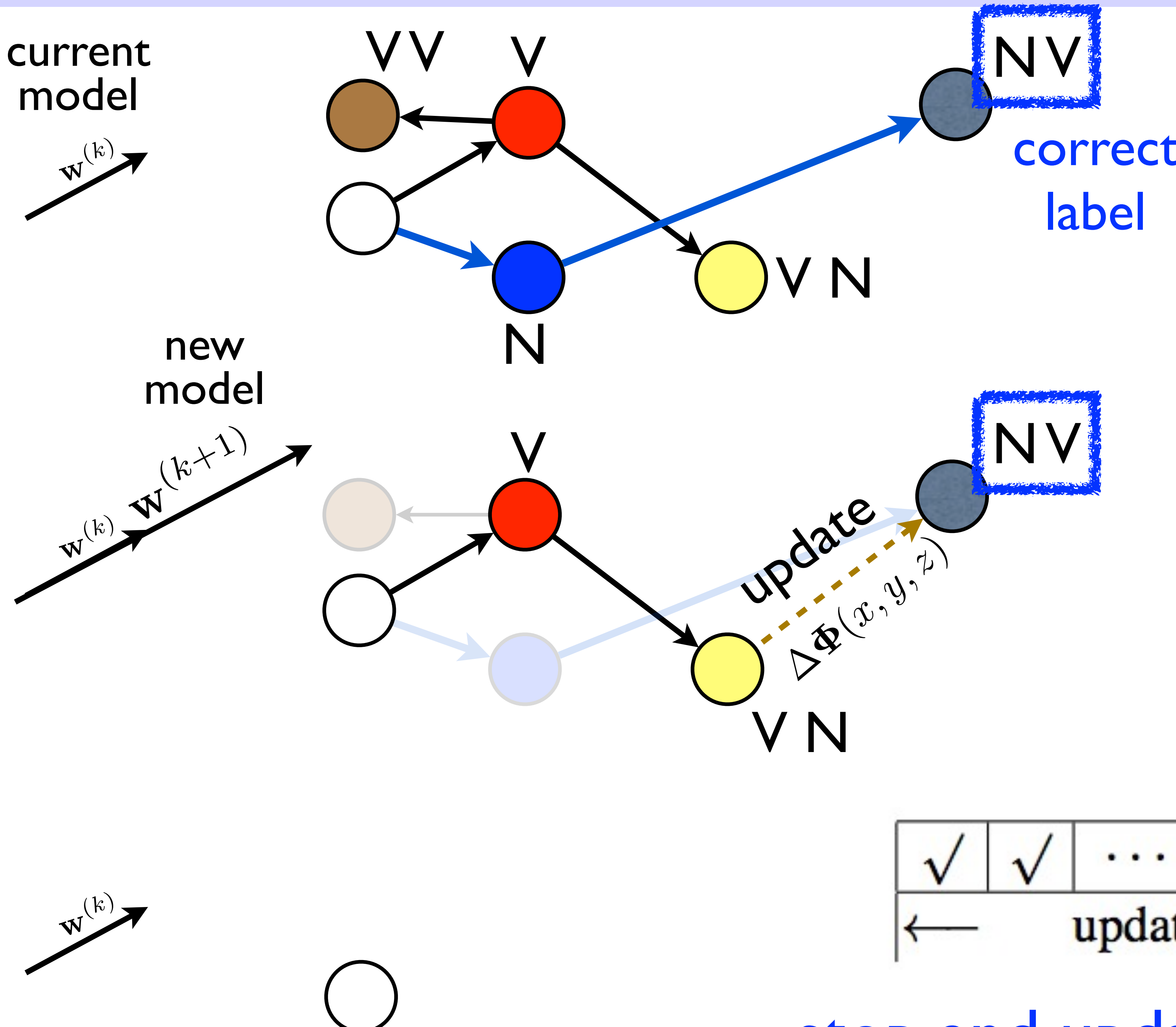
{N,V} x {N,V}

standard perceptron does not converge with greedy search

√	√	···	√	×	
⟵	update			⟶	skip ⟶

stop and update at the first mistake

Early update (Collins/Roark 2004) to rescue



training example

time flies

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output space

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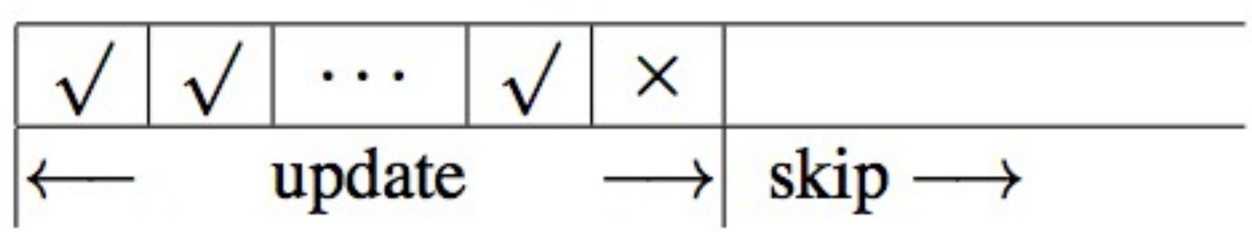

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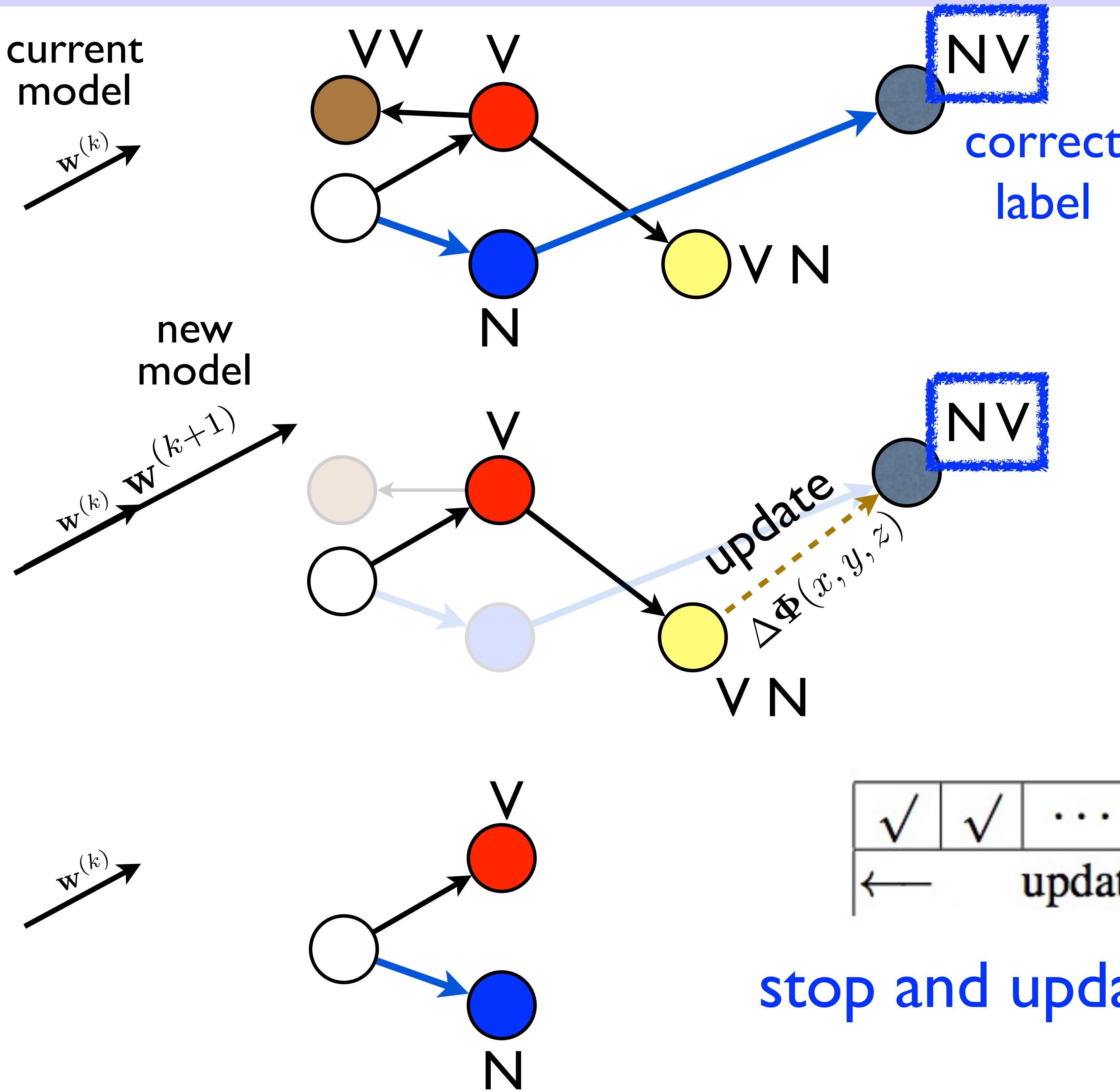


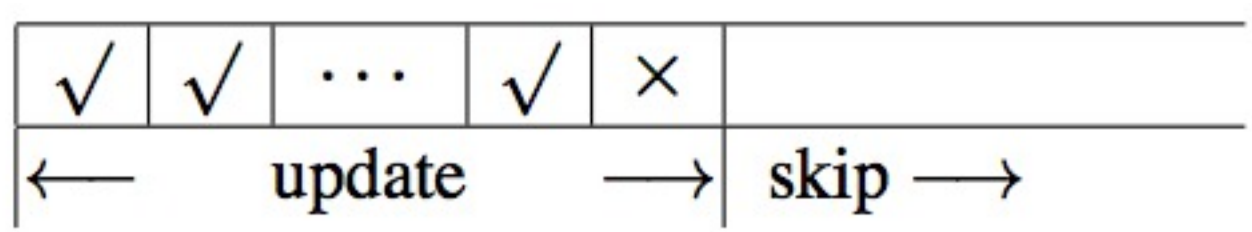
training example

time	flies
N	V

output space

{N,V} x {N,V}

standard perceptron does not converge with greedy search



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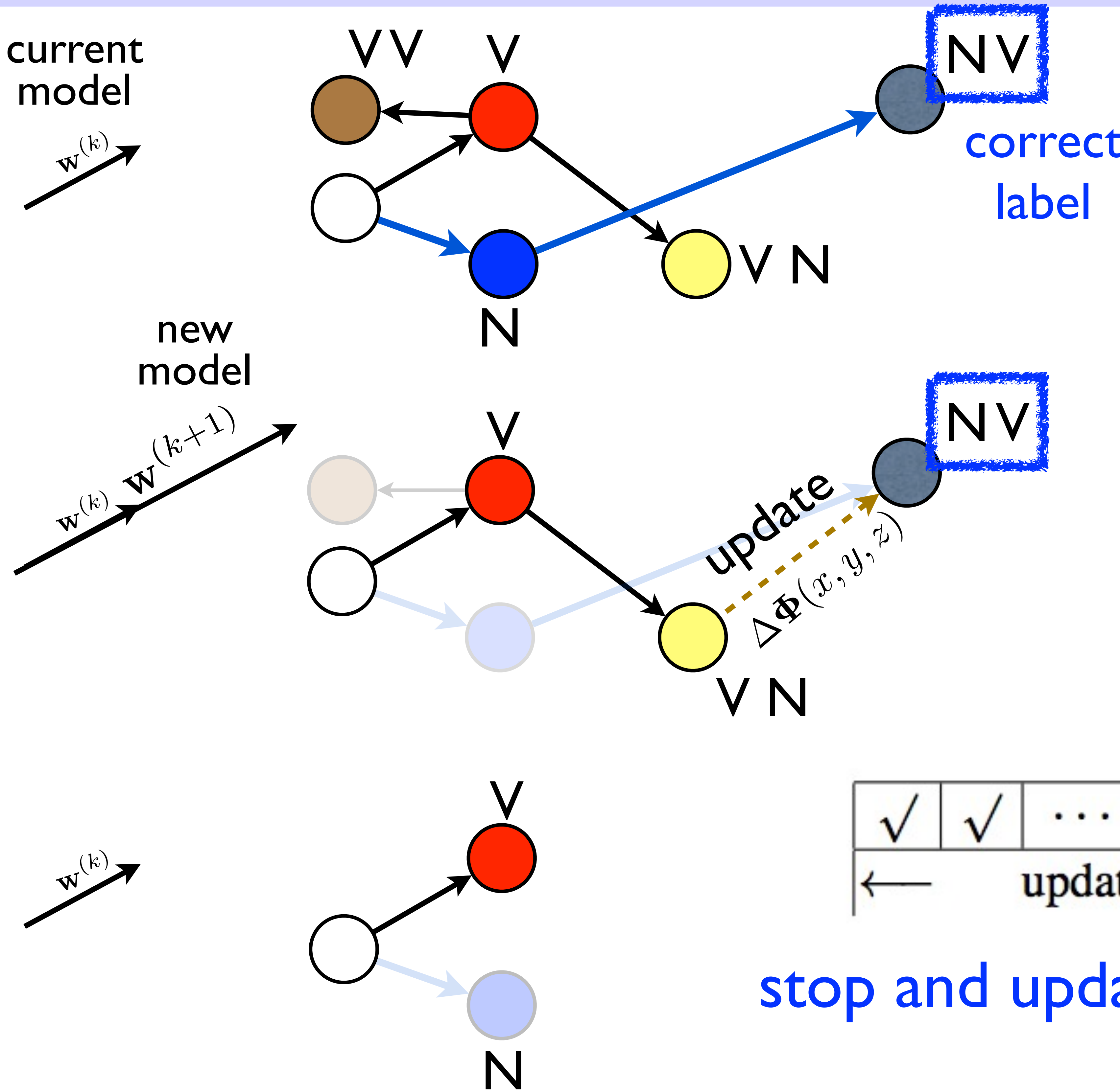

training example

time	flies
N	V

output space

{N,V} x {N,V}

standard perceptron does not converge with greedy search

√	√	· · ·	√	×	
⟵	update			⟶	skip ⟶

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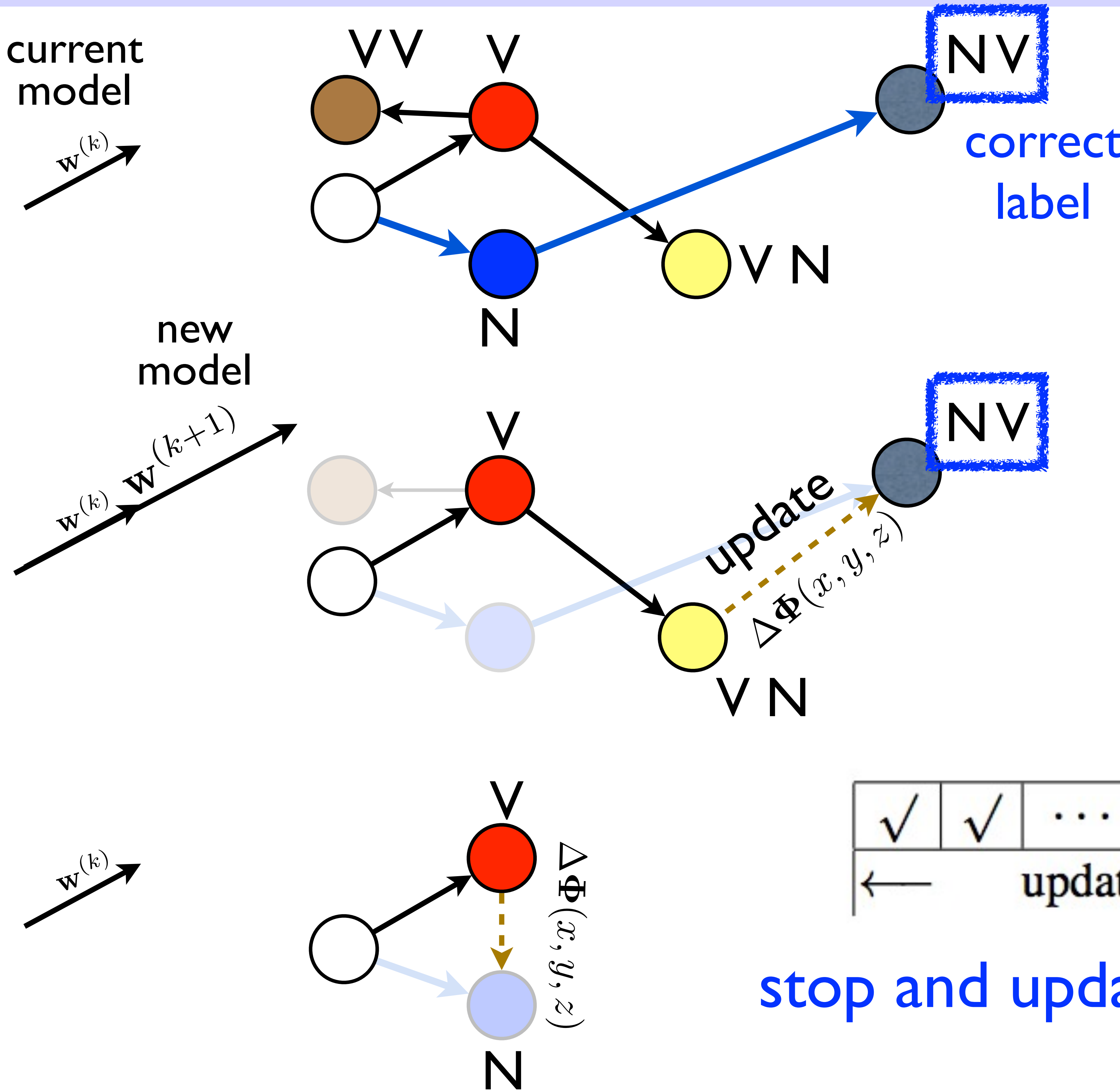


training example

time	flies
N	V

output space

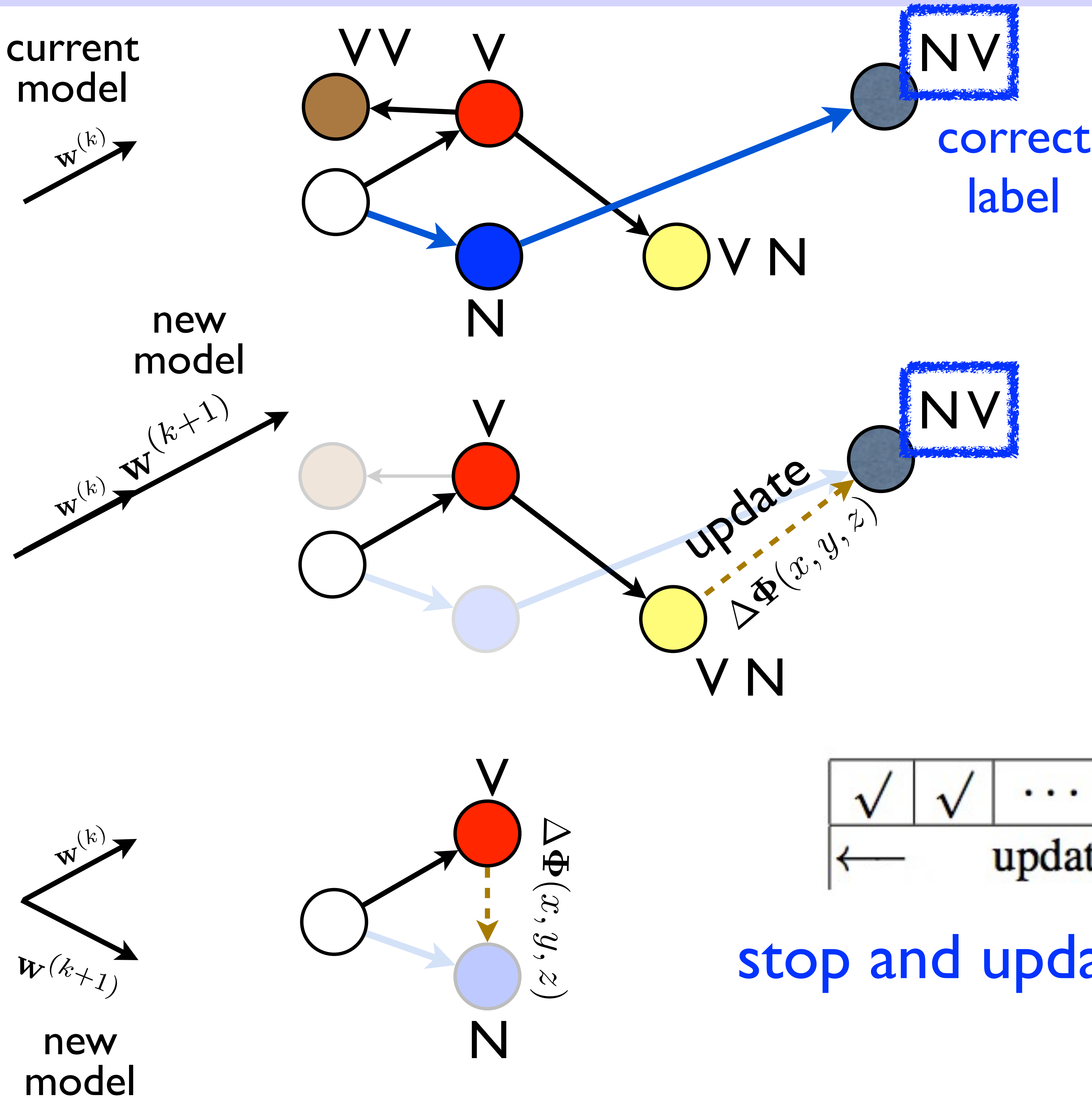
{N,V} x {N,V}

standard perceptron does not converge with greedy search

$\surd$	$\surd$	$\cdots$	$\surd$	$\times$	
$\longleftarrow$ update $\longrightarrow$					skip $\longrightarrow$

stop and update at the first mistake

Early update (Collins/Roark 2004) to rescue



training example

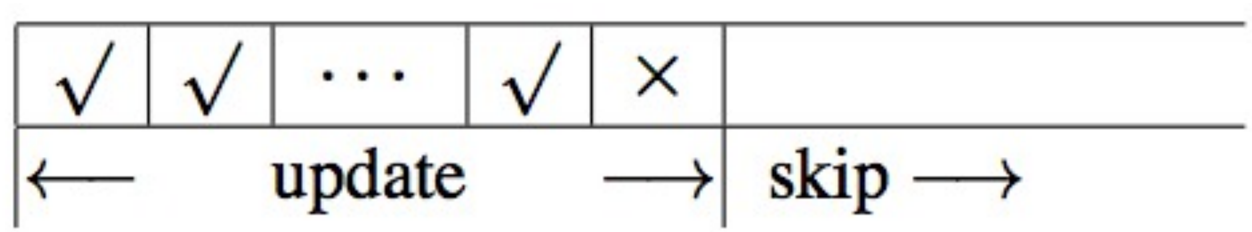
time flies

N V

output space

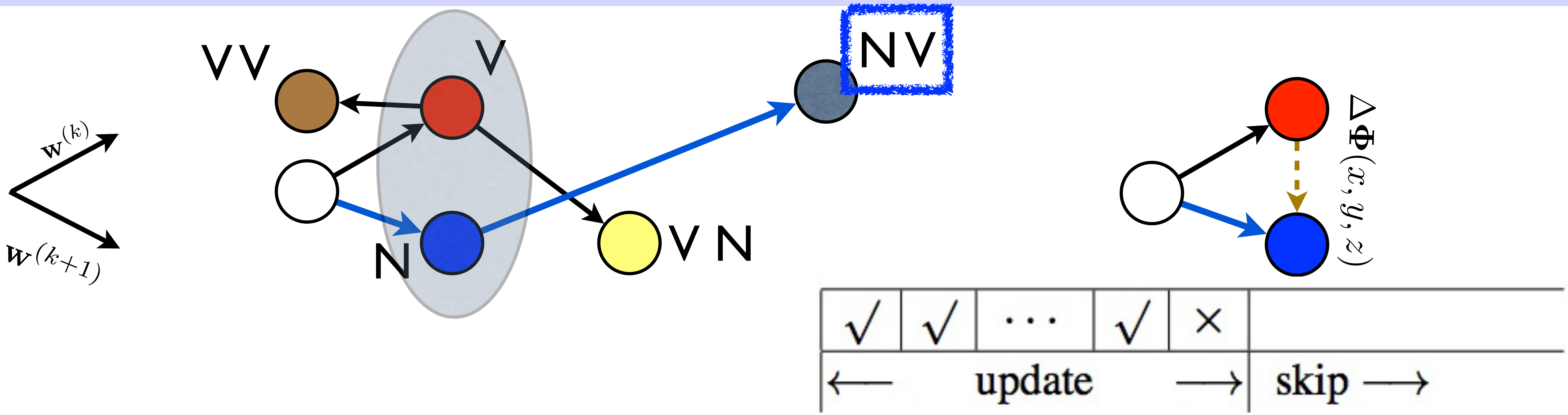
{N,V} x {N,V}

standard perceptron does not converge with greedy search



stop and update at the first mistake

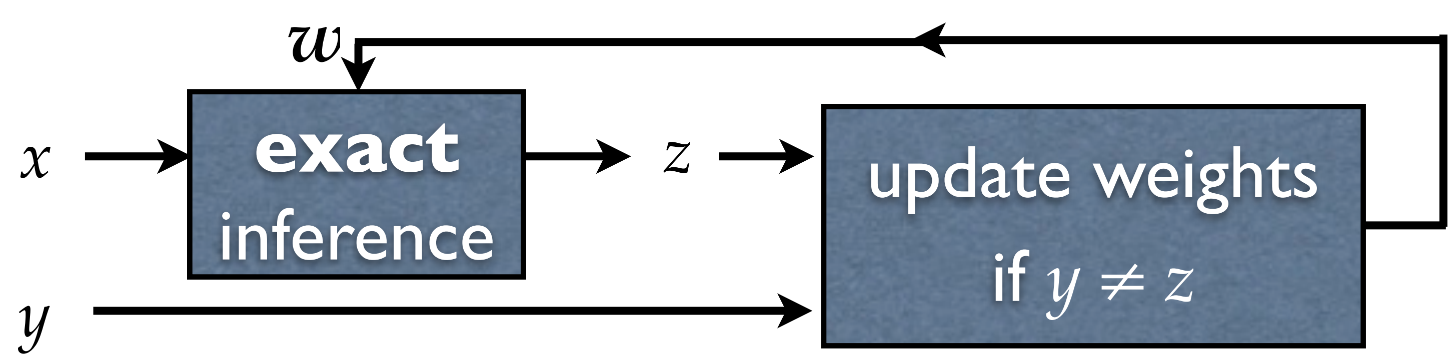
Why?

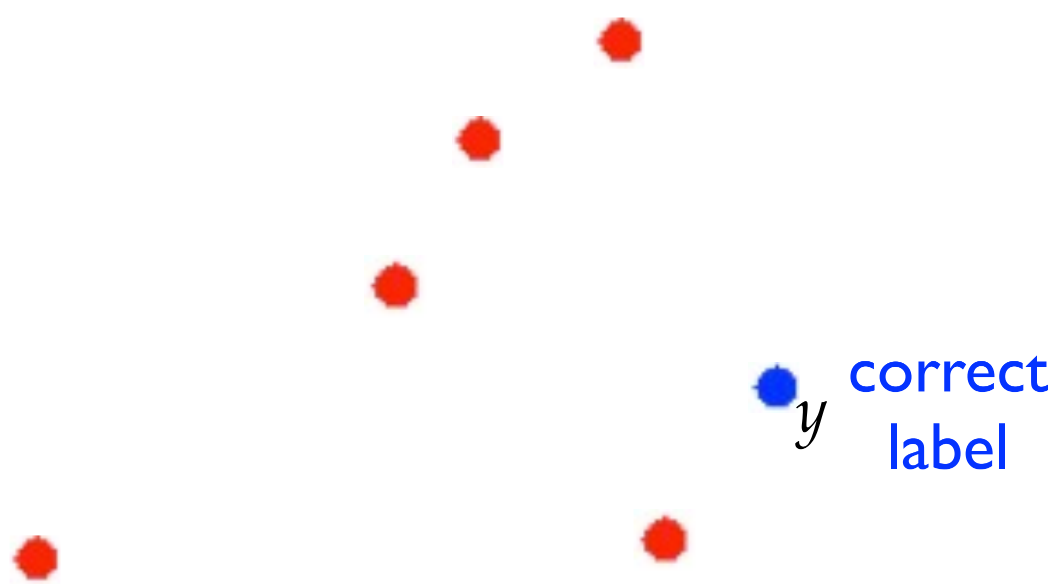


- why does inexact search break convergence property?
  - what is required for convergence? exactness?
- why does early update (Collins/Roark 04) work?
  - it works well in practice and is now a standard method
  - but there has been no theoretical justification
- we answer these Qs by inspecting the convergence proof

Geometry of Convergence Proof pt 1

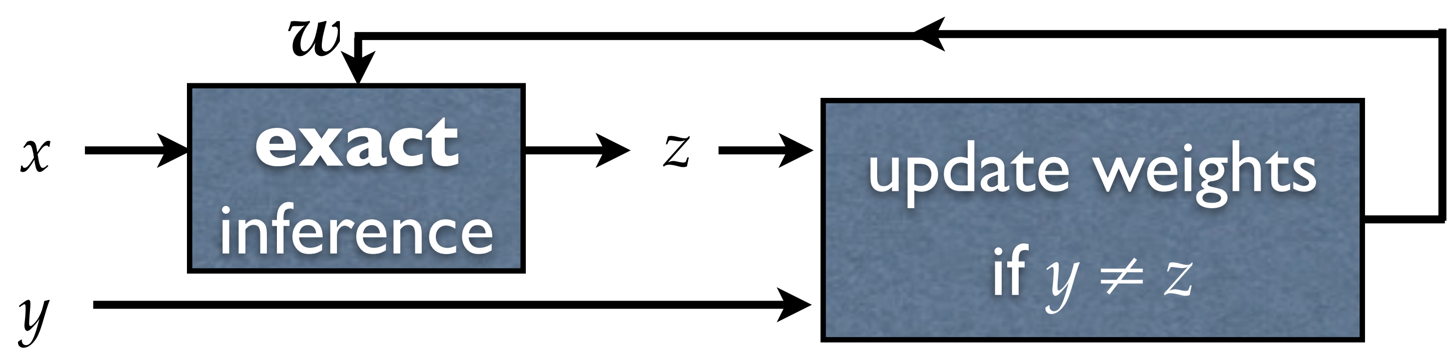
repeat
  for each example (x, y) **in** D **do**
    $z \leftarrow \textsc{Exact}(x, \mathbf{w})$
    if $z \neq y$ **then**
      $\mathbf{w} \leftarrow \mathbf{w} + \Delta\mathbf{\Phi}(x, y, z)$
until converged

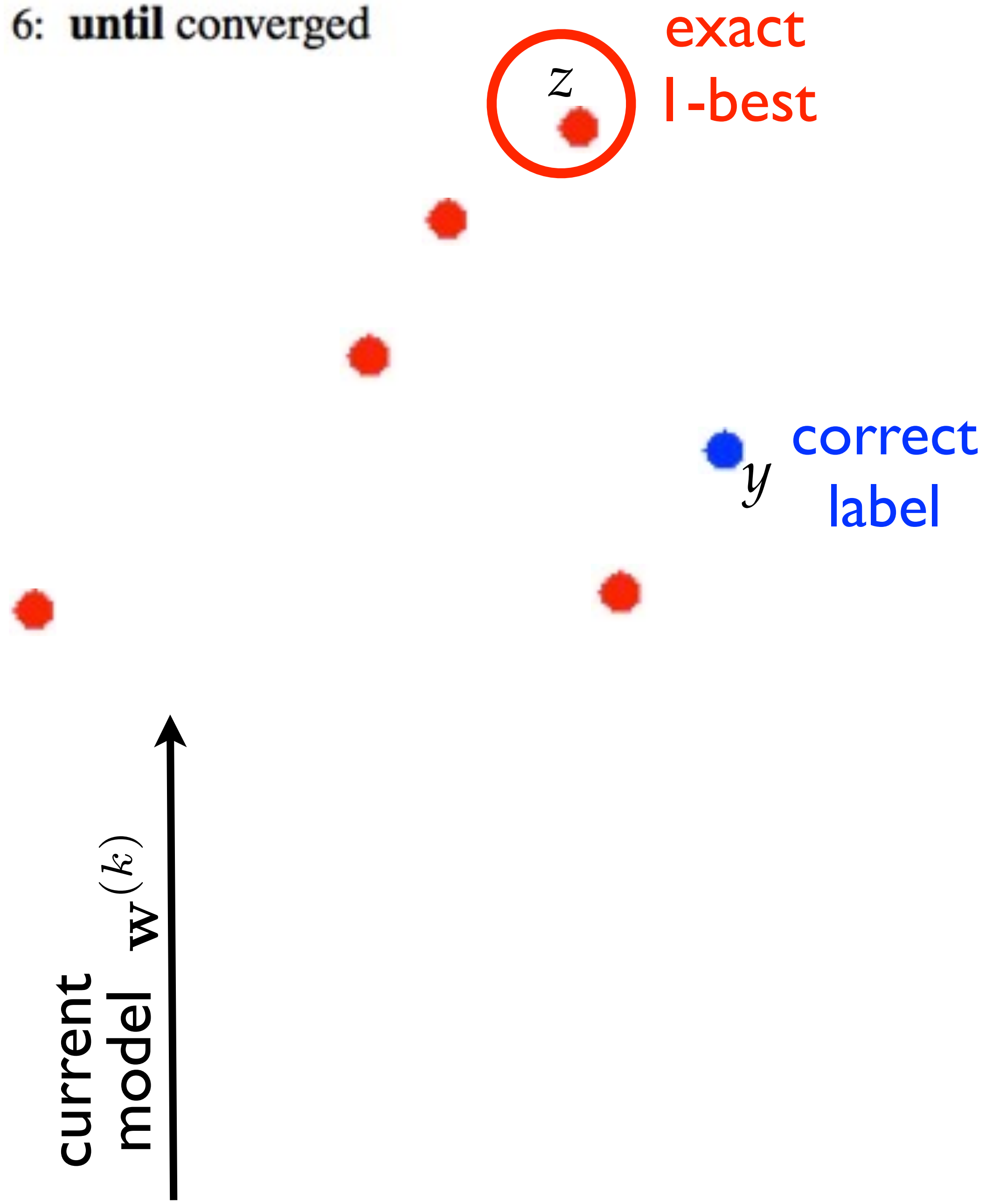




Geometry of Convergence Proof pt 1

```
repeat
    for each example (x, y) in D do
        z ← EXACT(x, w)
        if z ≠ y then
            w ← w + ΔΦ(x, y, z)
until converged
```





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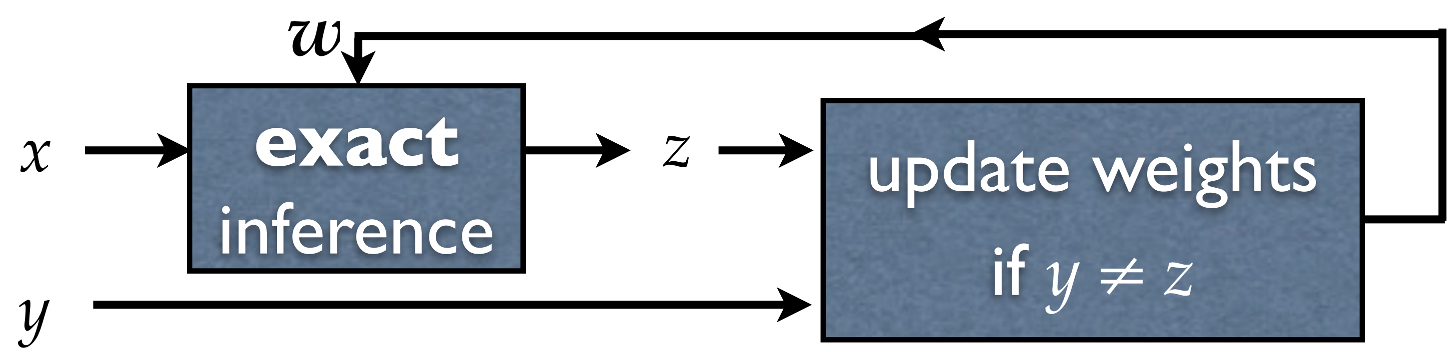

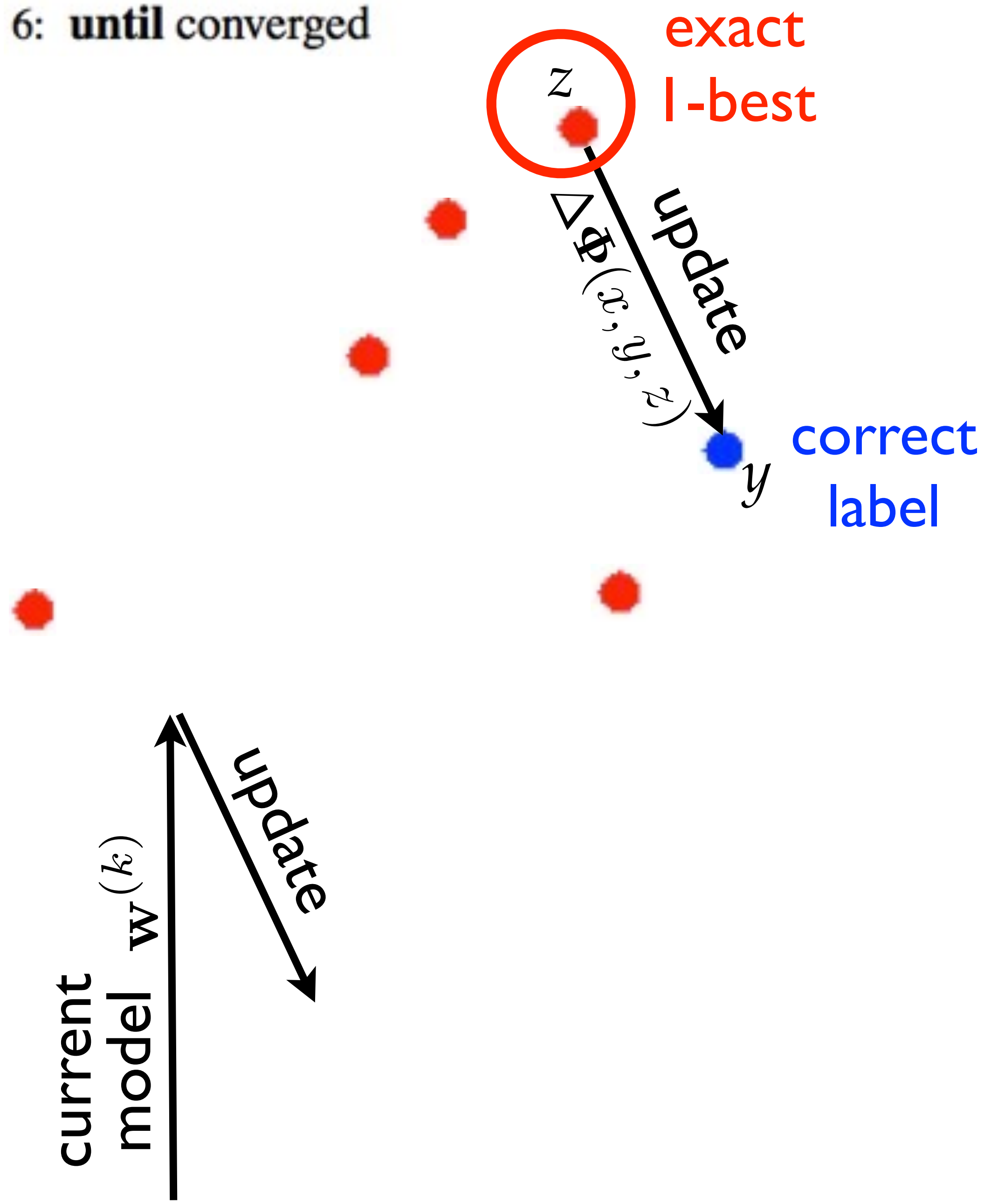

perceptron update:

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$

Geometry of Convergence Proof pt 1

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    $z \leftarrow \textsc{Exact}(x, \mathbf{w})$
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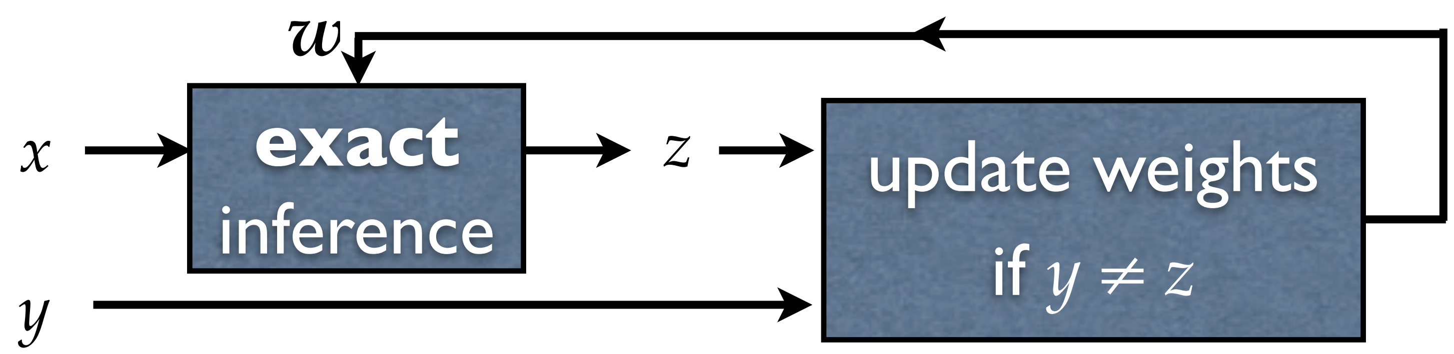
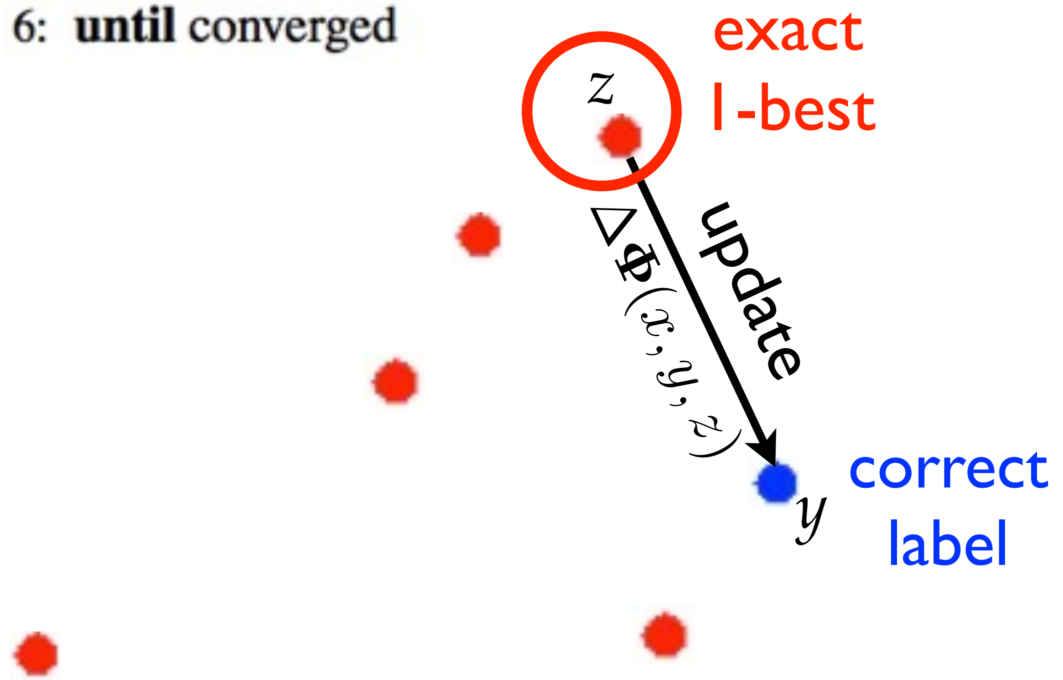
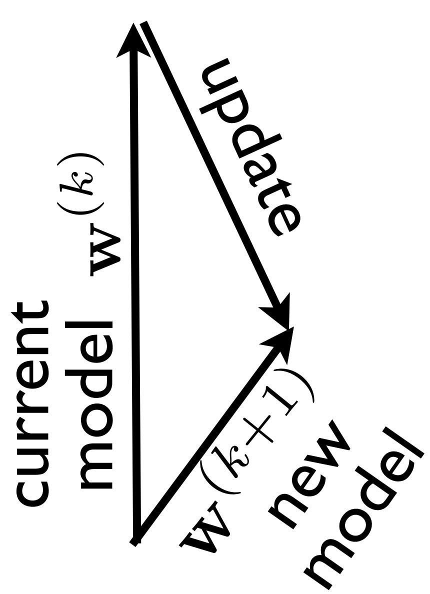




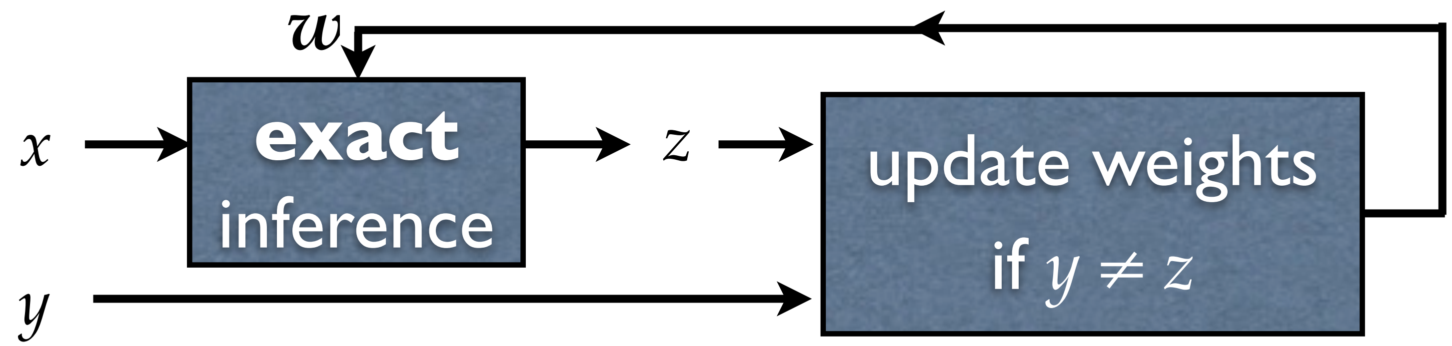
perceptron update:

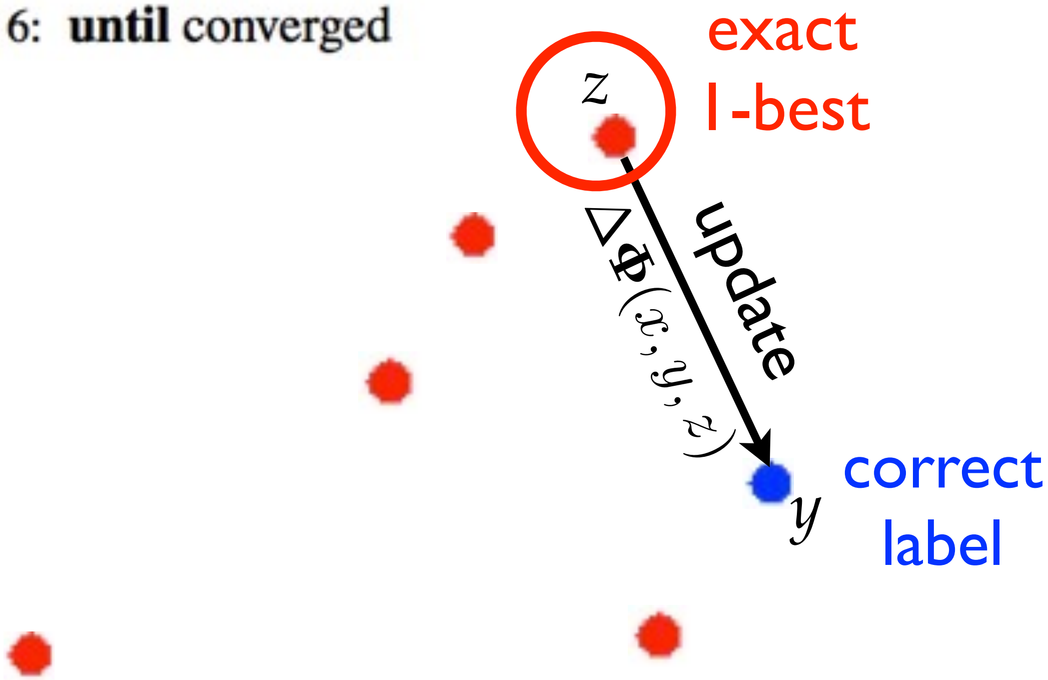
$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$



Geometry of Convergence Proof pt 1

1: **repeat**
2: **for each** example (x, y) **in** D **do**
3: $z \leftarrow \textsc{Exact}(x, \mathbf{w})$
4: **if** $z \neq y$ **then**
5: $\mathbf{w} \leftarrow \mathbf{w} + \Delta\mathbf{\Phi}(x, y, z)$
6: **until** converged

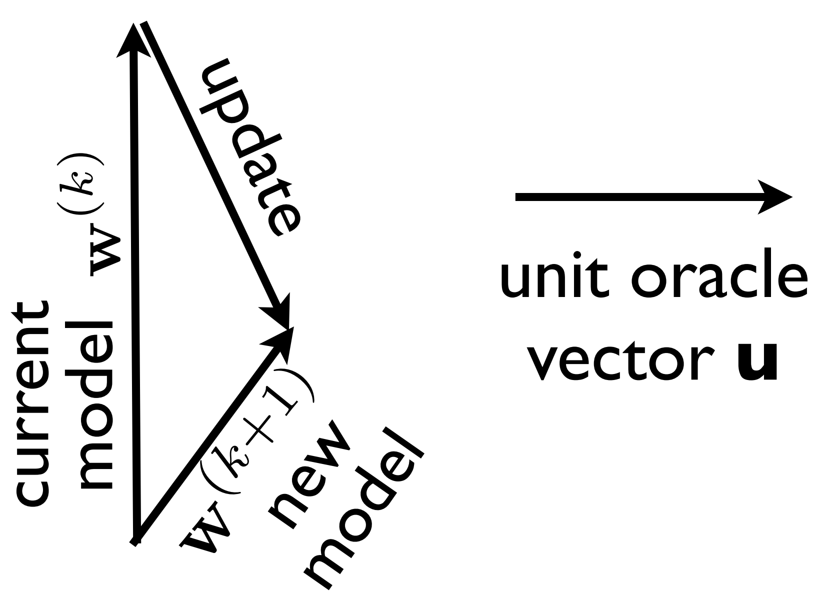




perceptron update:

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$

$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} = \mathbf{u} \cdot \mathbf{w}^{(k)} + \mathbf{u} \cdot \Delta\mathbf{\Phi}(x, y, z)$$



Geometry of Convergence Proof pt 1

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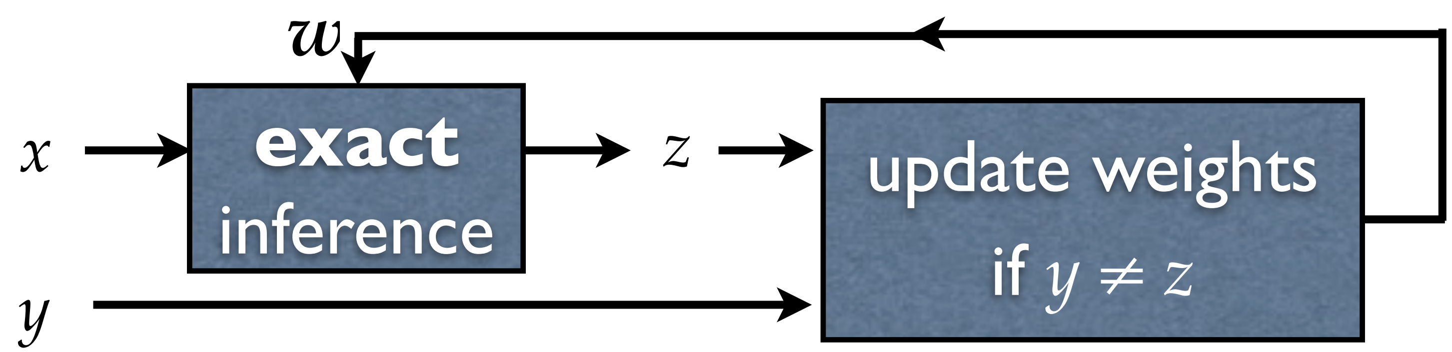
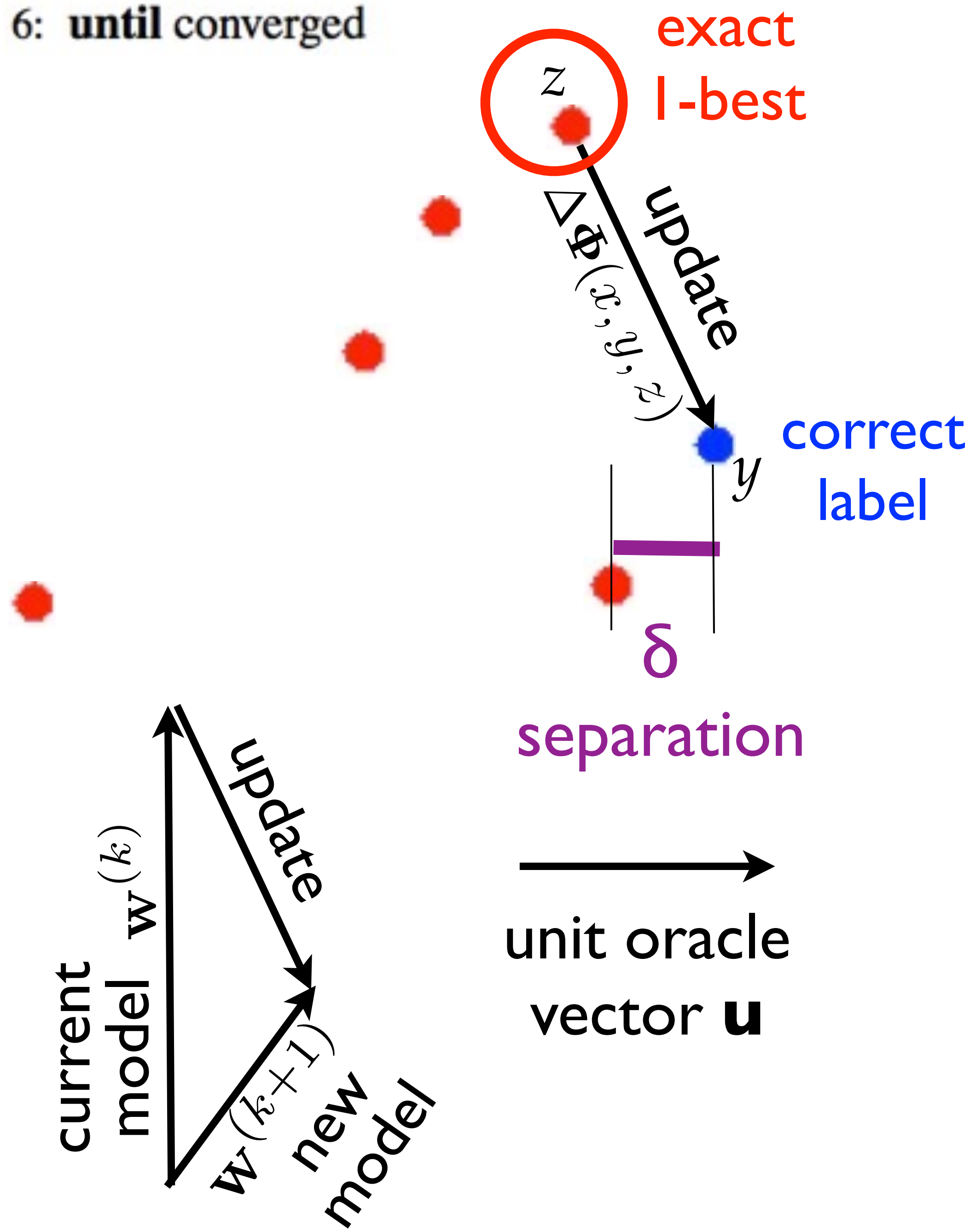
2: **for each** example (x, y) **in** D **do**
3: $z \leftarrow \textsc{Exact}(x, \mathbf{w})$
4: **if** $z \neq y$ **then**
5: $\mathbf{w} \leftarrow \mathbf{w} + \Delta\mathbf{\Phi}(x, y, z)$
6: **until** converged





perceptron update:

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$

$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} = \mathbf{u} \cdot \mathbf{w}^{(k)} + \underbrace{\mathbf{u} \cdot \Delta\mathbf{\Phi}(x, y, z)}_{\geq \delta}$$

$\geq \delta$ margin

Geometry of Convergence Proof pt 1

repeat
  for each example (x, y) **in** D **do**
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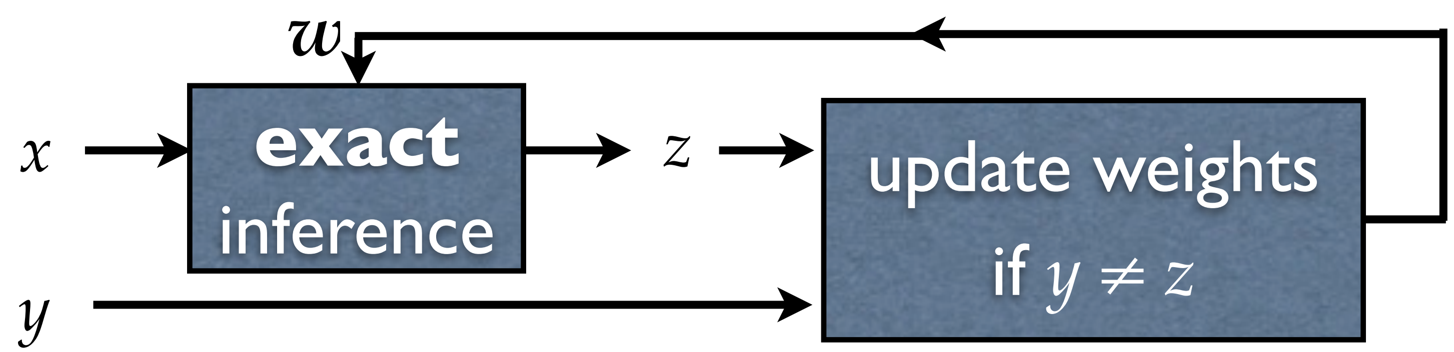

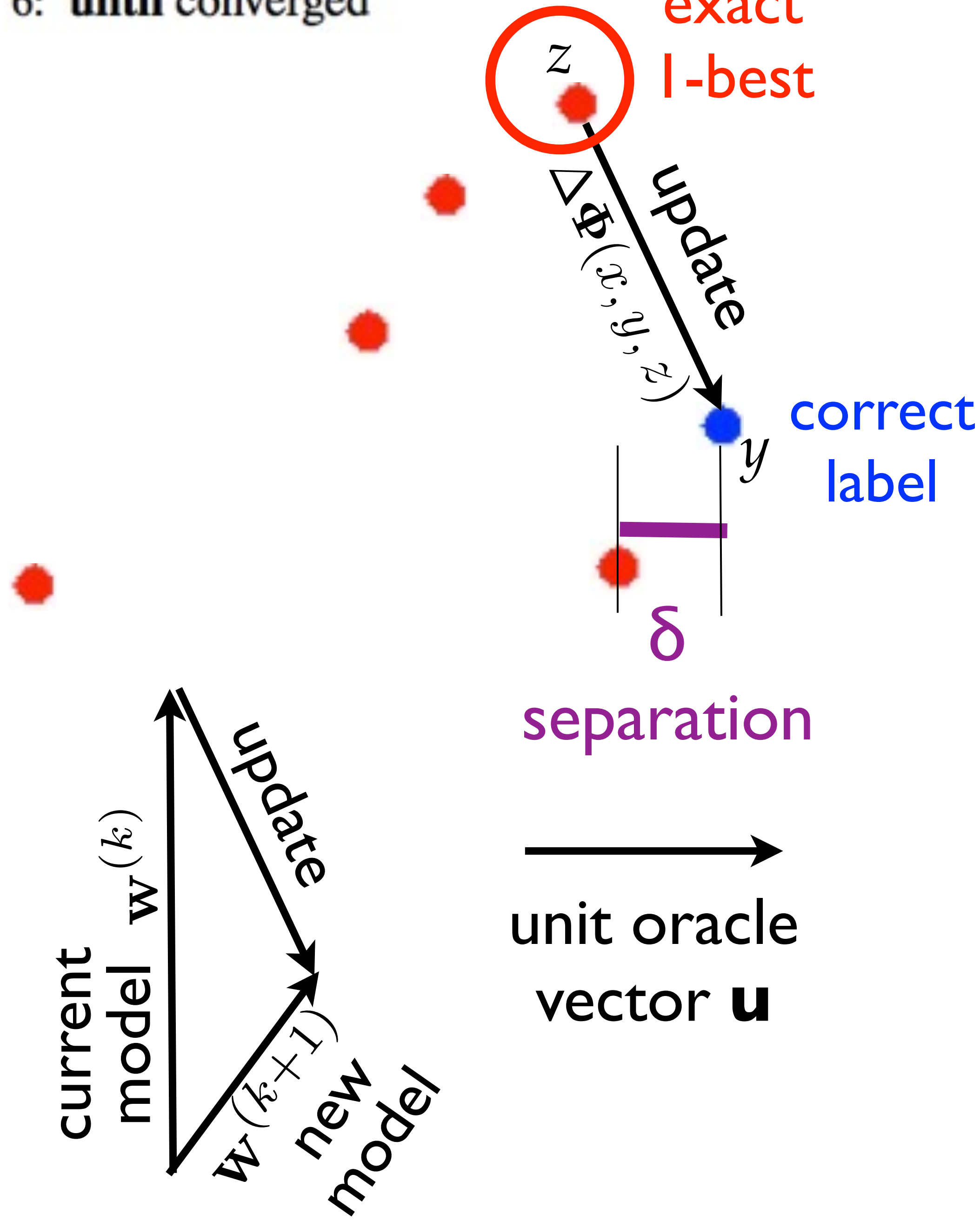

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$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} = \mathbf{u} \cdot \mathbf{w}^{(k)} + \boxed{\mathbf{u} \cdot \Delta\mathbf{\Phi}(x, y, z)}$$

$\geq \delta$ margin

$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} \geq k\delta \quad \text{(by induction)}$$

Geometry of Convergence Proof pt 1

repeat
  for each example (x, y) **in** D **do**
    $z \leftarrow \textsc{Exact}(x, \mathbf{w})$
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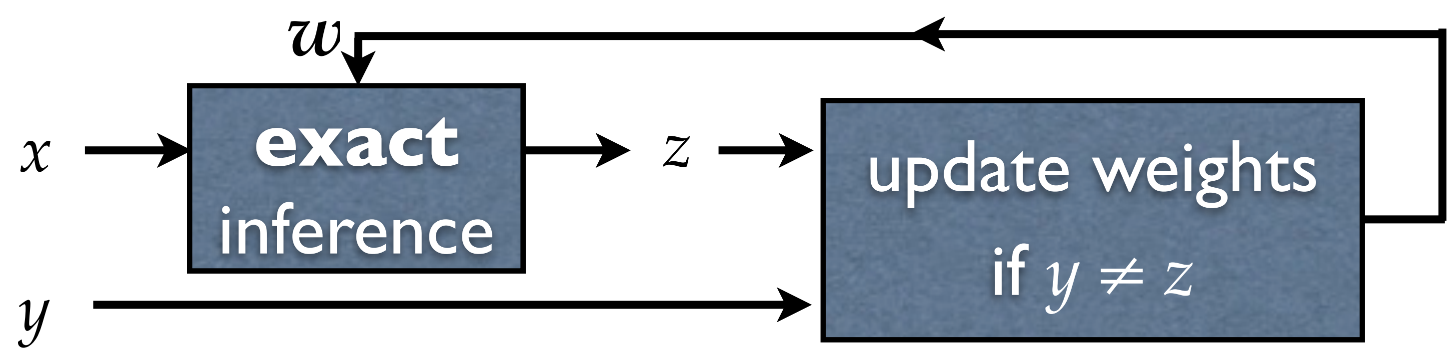

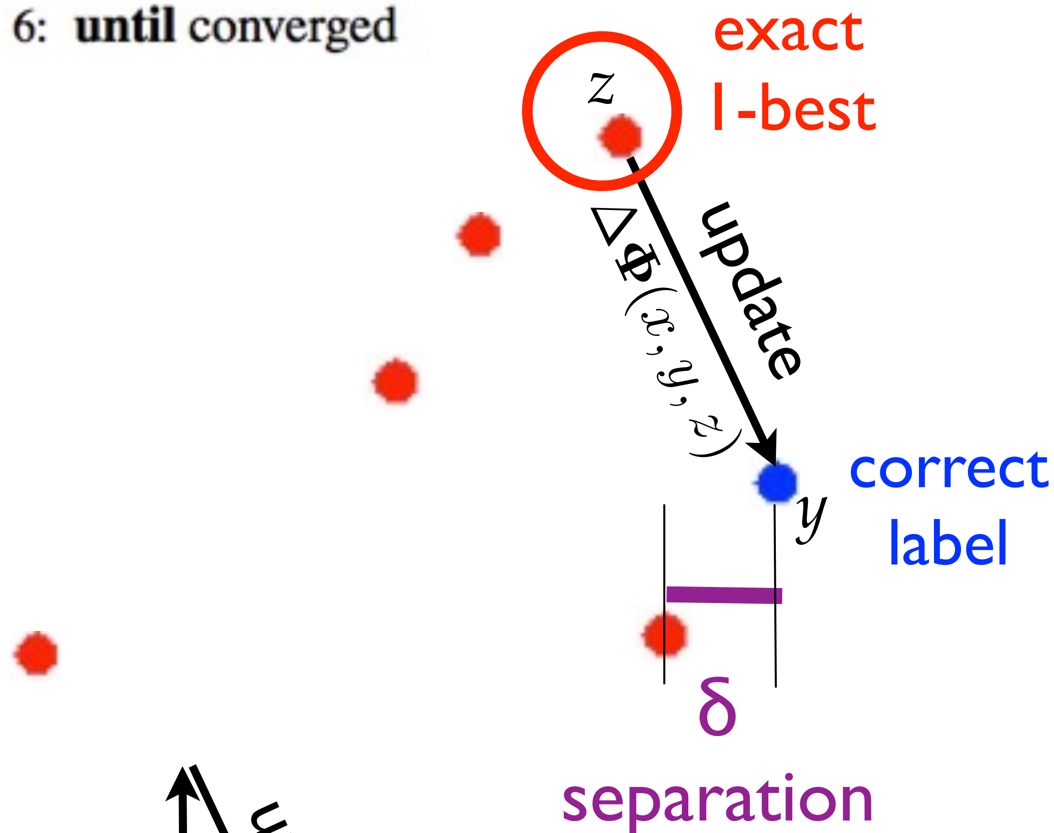

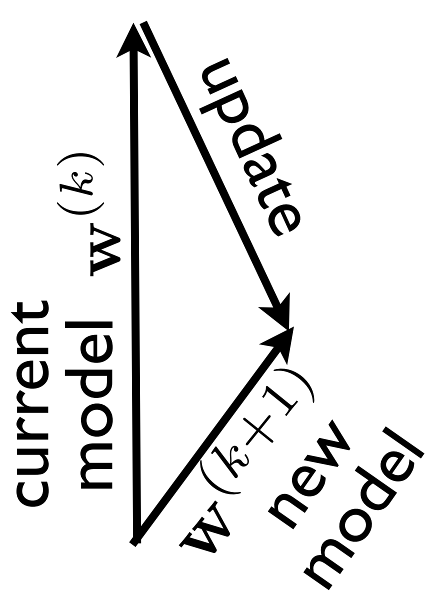

unit oracle vector **u**

perceptron update:

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$

$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} = \mathbf{u} \cdot \mathbf{w}^{(k)} + \boxed{\mathbf{u} \cdot \Delta\mathbf{\Phi}(x, y, z) \geq \delta} \quad \text{margin}$$

$$\mathbf{u} \cdot \mathbf{w}^{(k+1)} \geq k\delta \qquad \text{(by induction)}$$

$$\|\mathbf{u}\| \|\mathbf{w}^{(k+1)}\| \geq \mathbf{u} \cdot \mathbf{w}^{(k+1)} \geq k\delta$$

$$\|\mathbf{w}^{(k+1)}\| \geq k\delta \qquad \text{(part 1: upperbound)}$$

Geometry of Convergence Proof pt 2

repeat
  for each example (x, y) **in** D **do**
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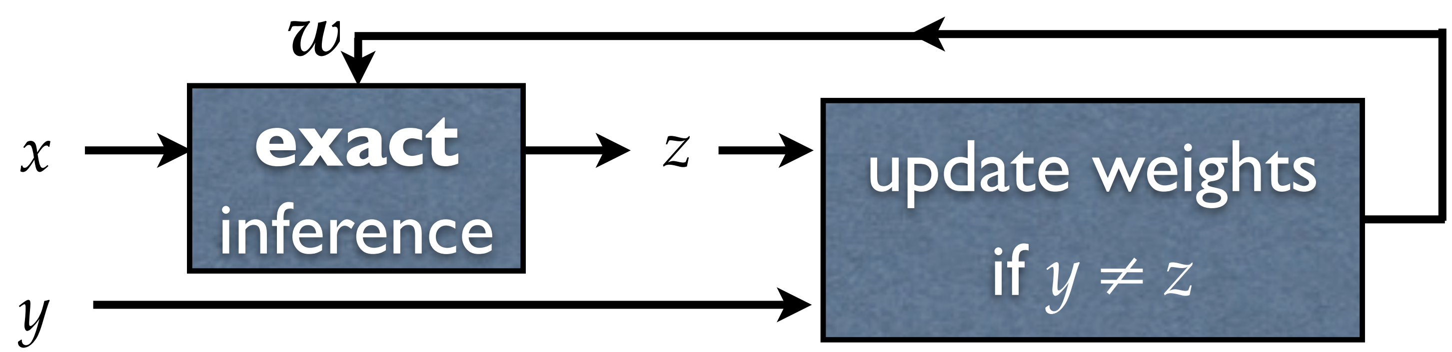

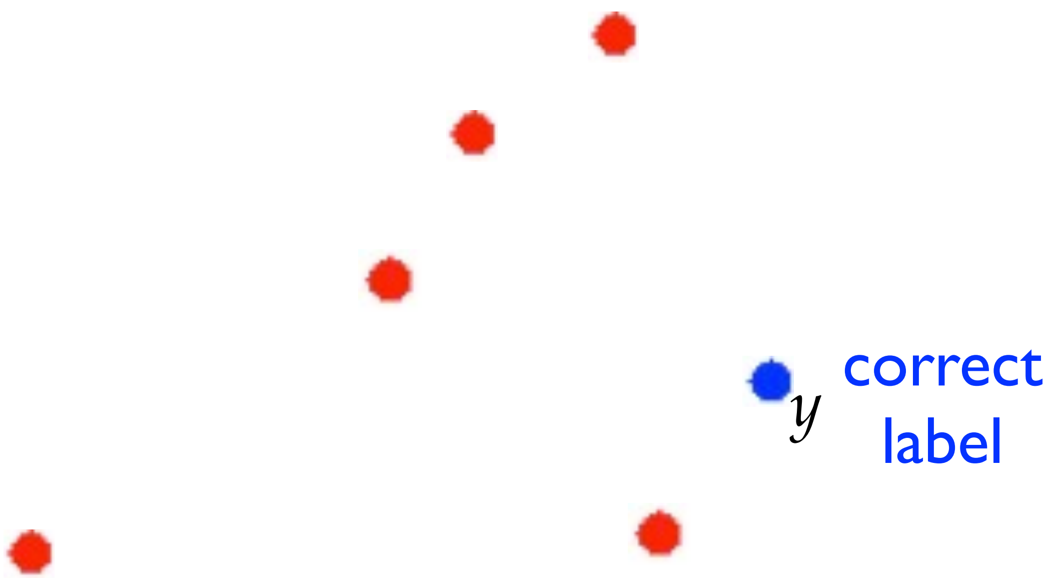

Geometry of Convergence Proof pt 2

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repeat
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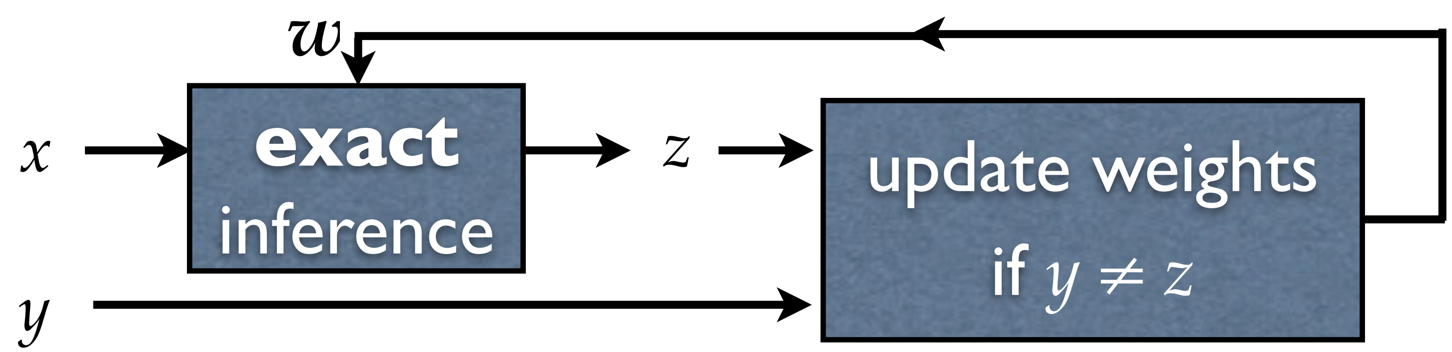

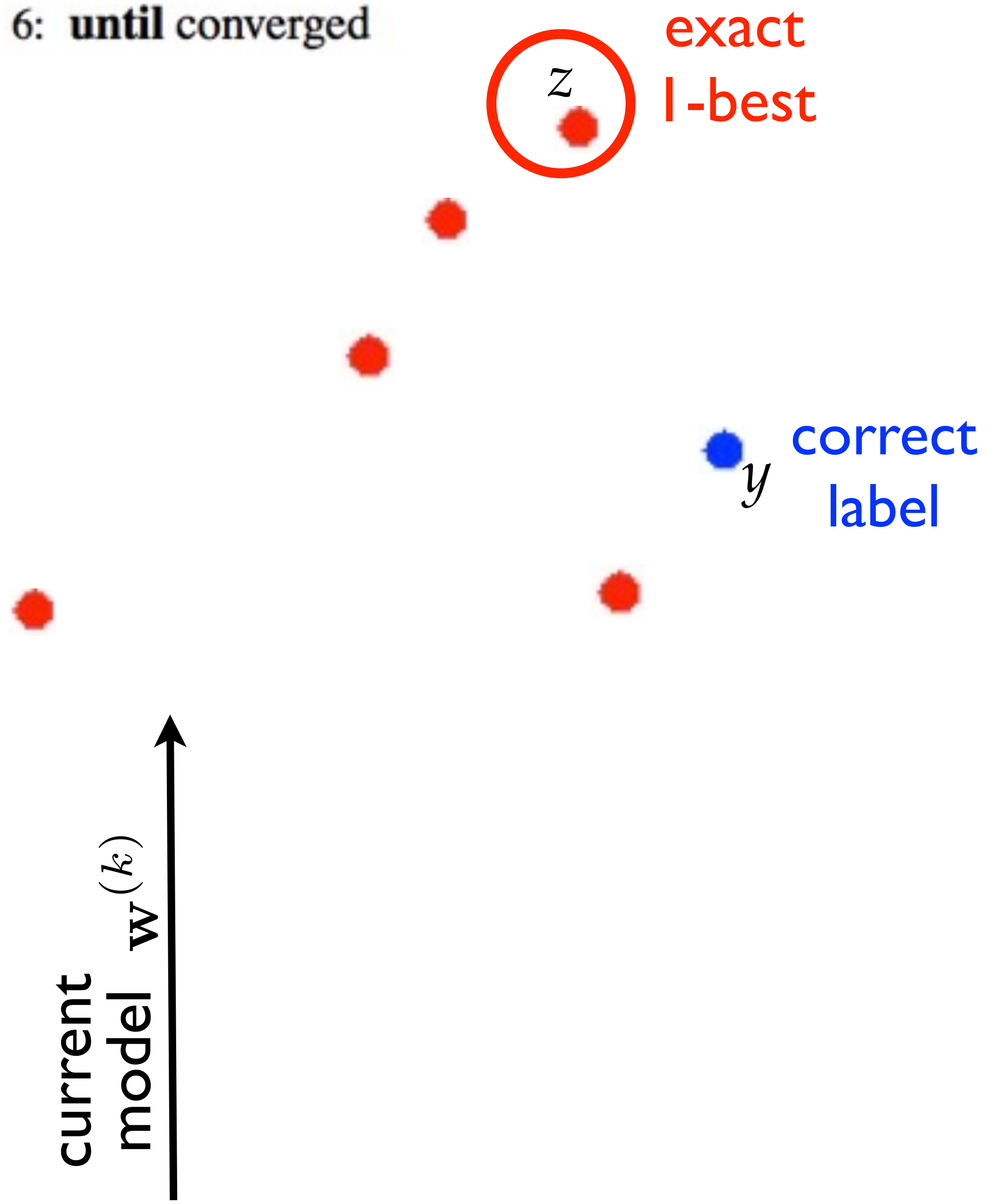

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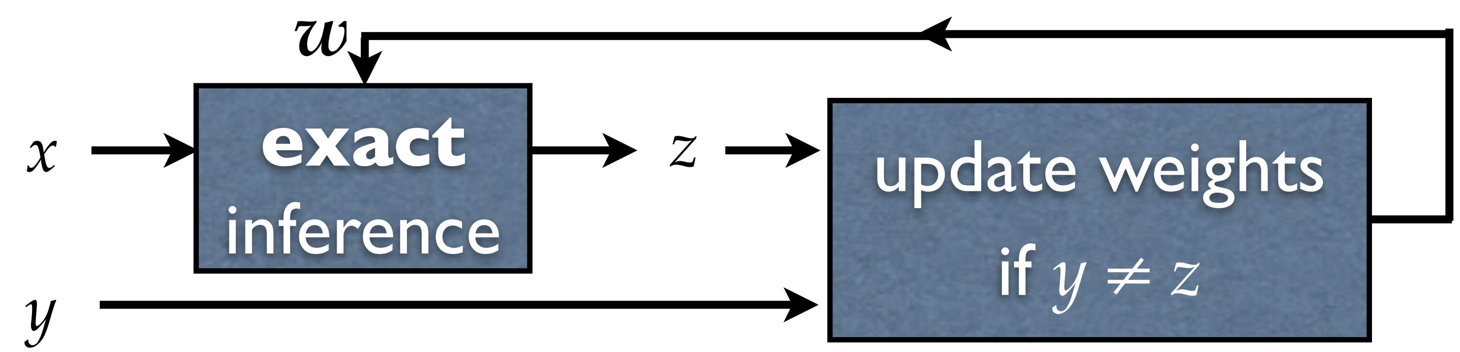

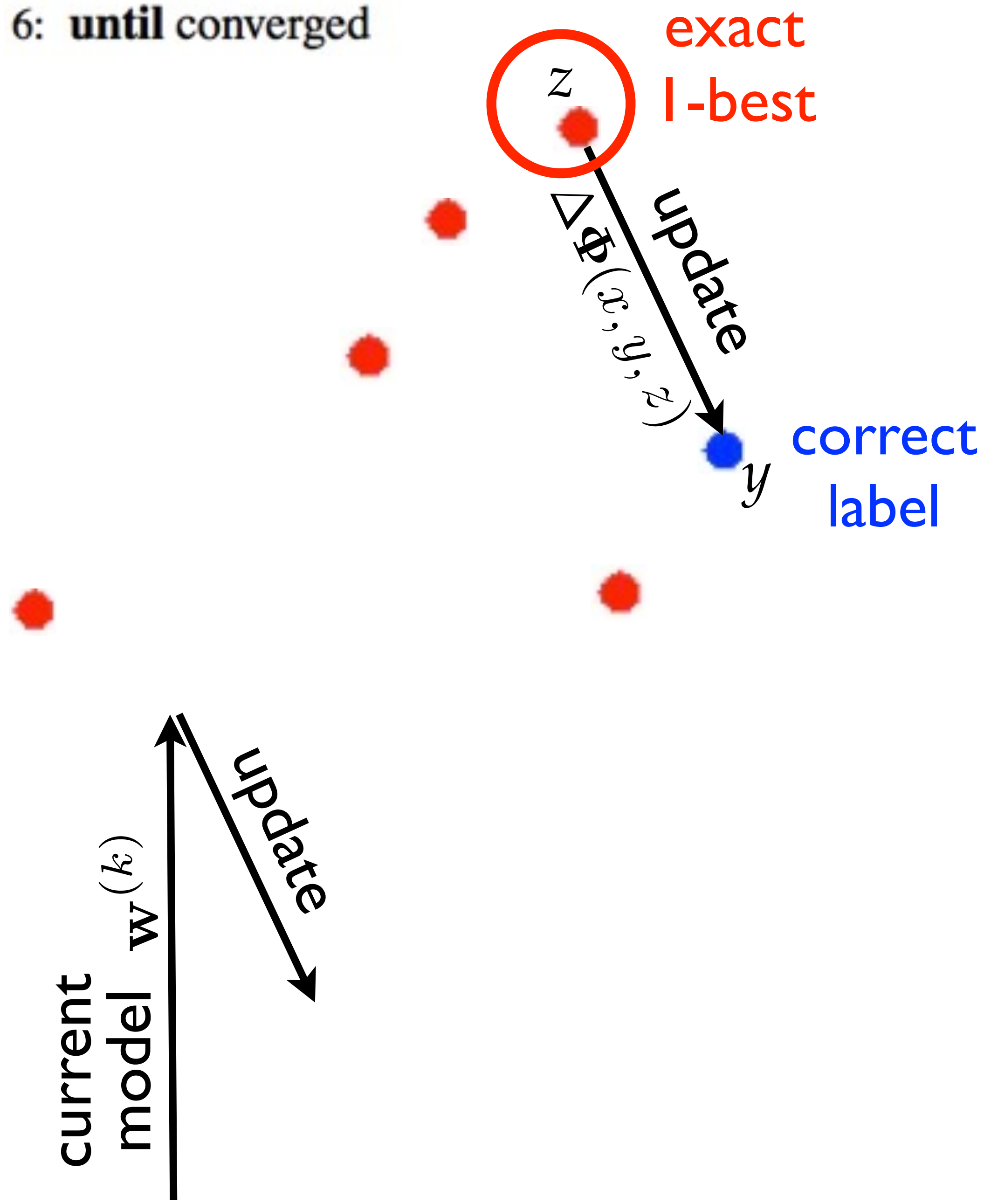

perceptron update:

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \Delta\mathbf{\Phi}(x, y, z)$$

Geometry of Convergence Proof pt 2

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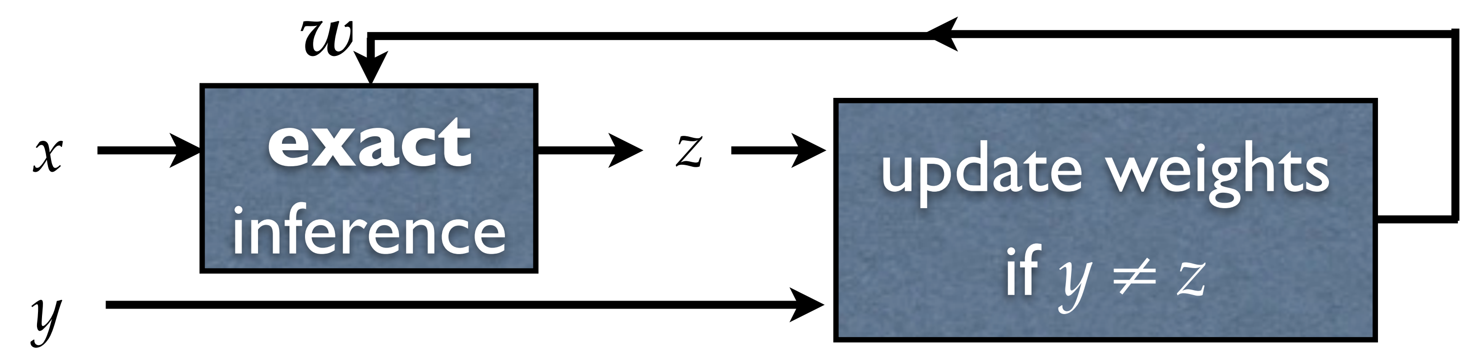

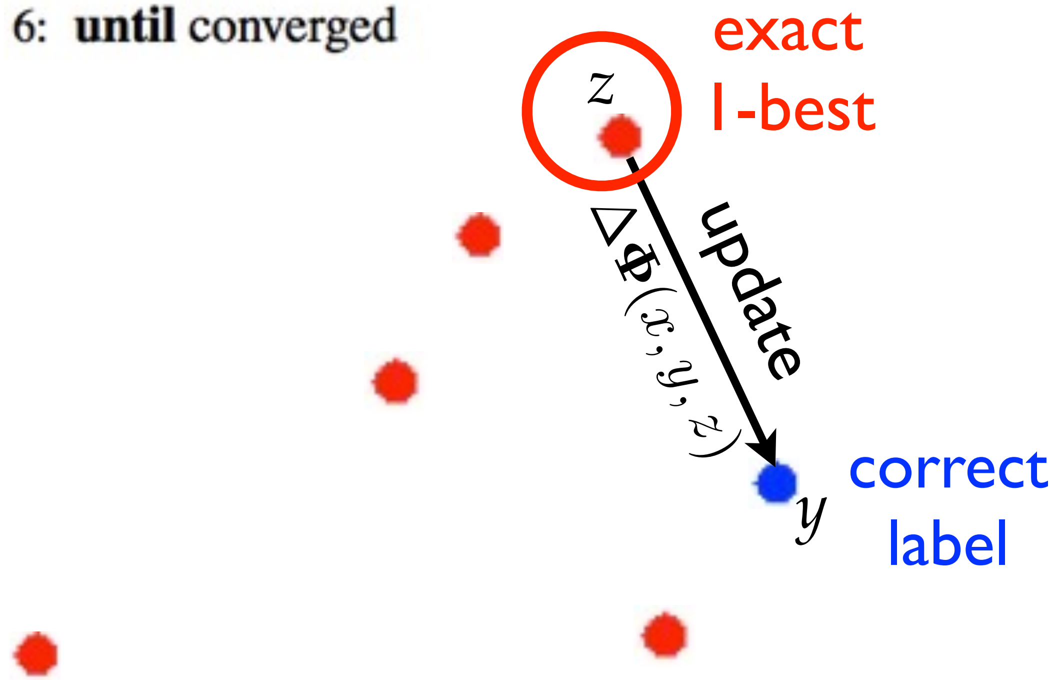

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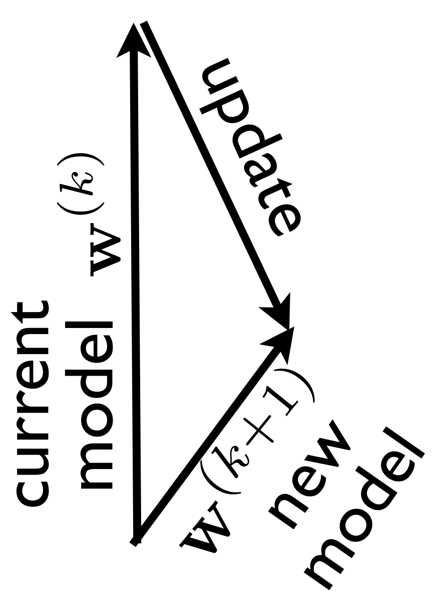

Geometry of Convergence Proof pt 2

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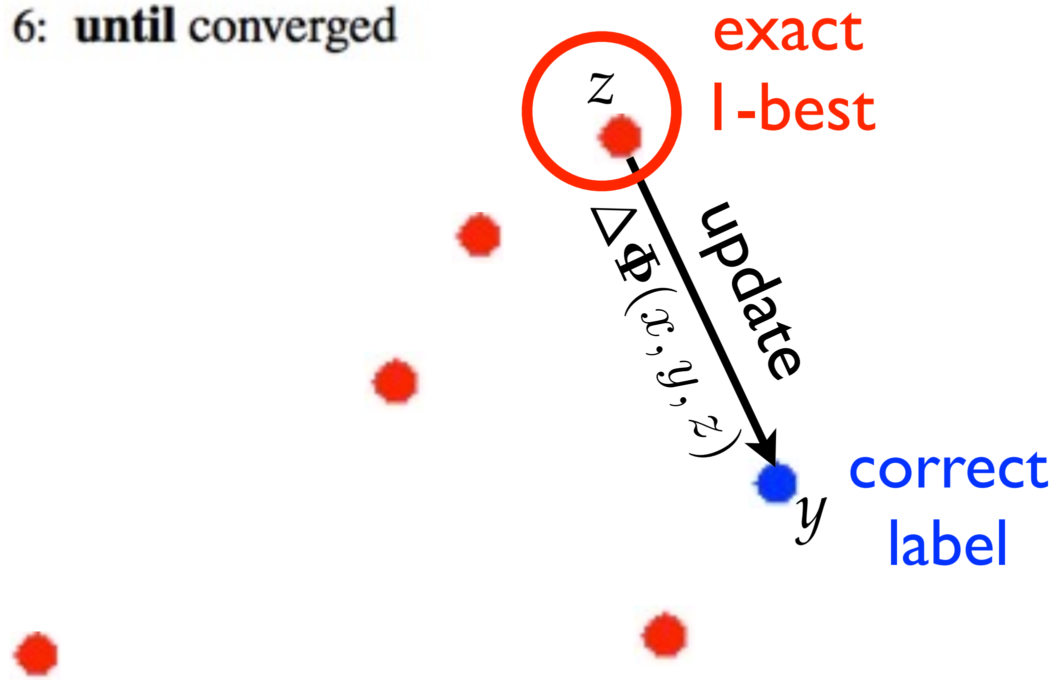

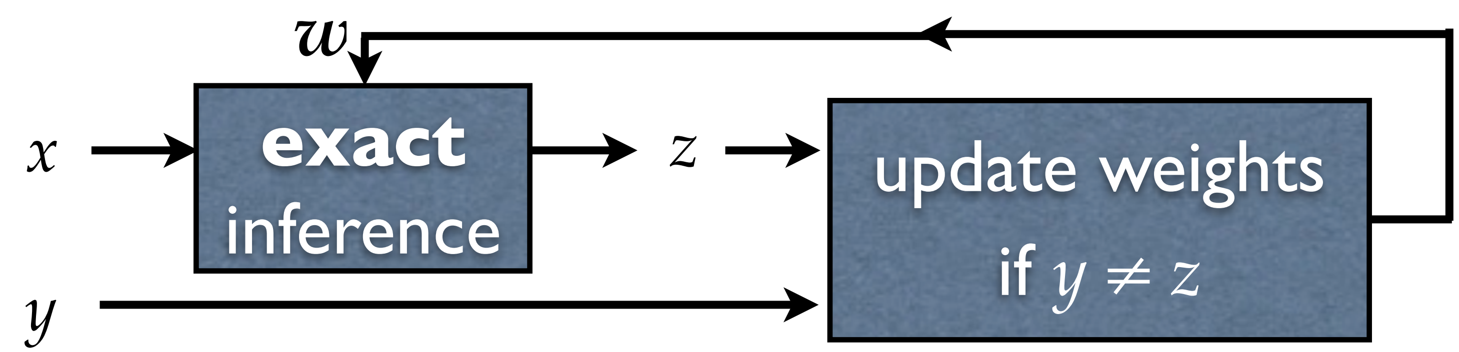

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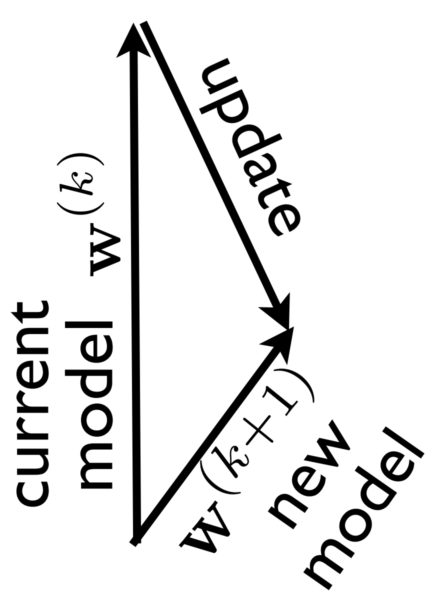
$$\|\mathbf{w}^{(k+1)}\|^2 = \|\mathbf{w}^{(k)} + \Delta\boldsymbol{\Phi}(x, y, z)\|^2$$



Geometry of Convergence Proof pt 2

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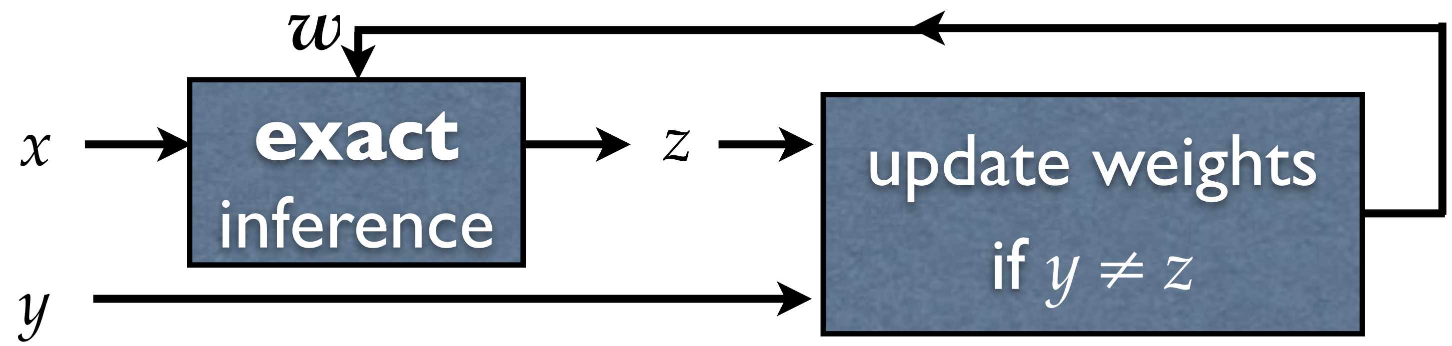
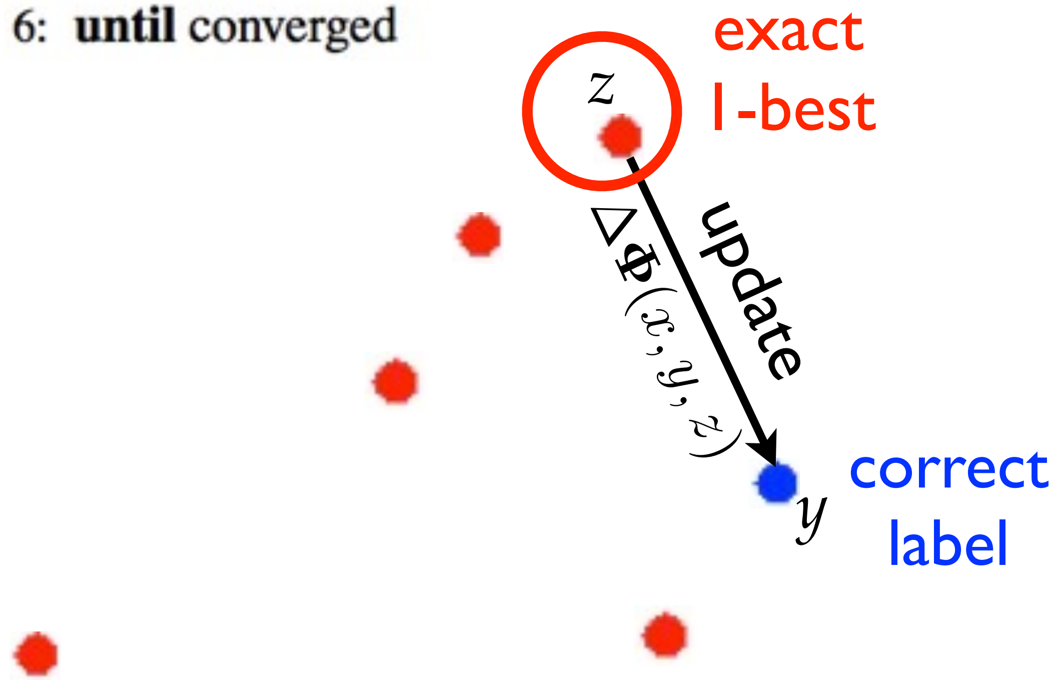
```





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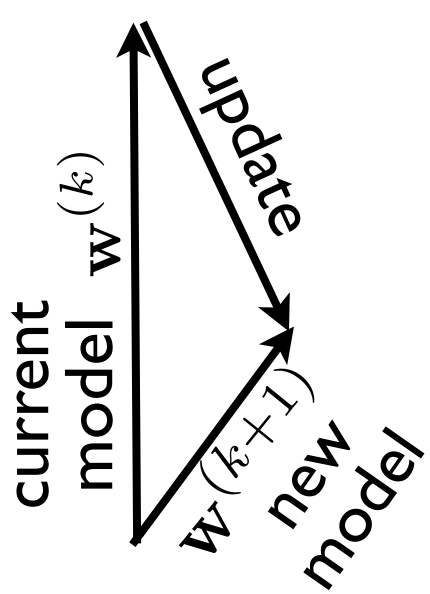
$$= \|\mathbf{w}^{(k)}\|^2 + \|\Delta\Phi(x, y, z)\|^2$$



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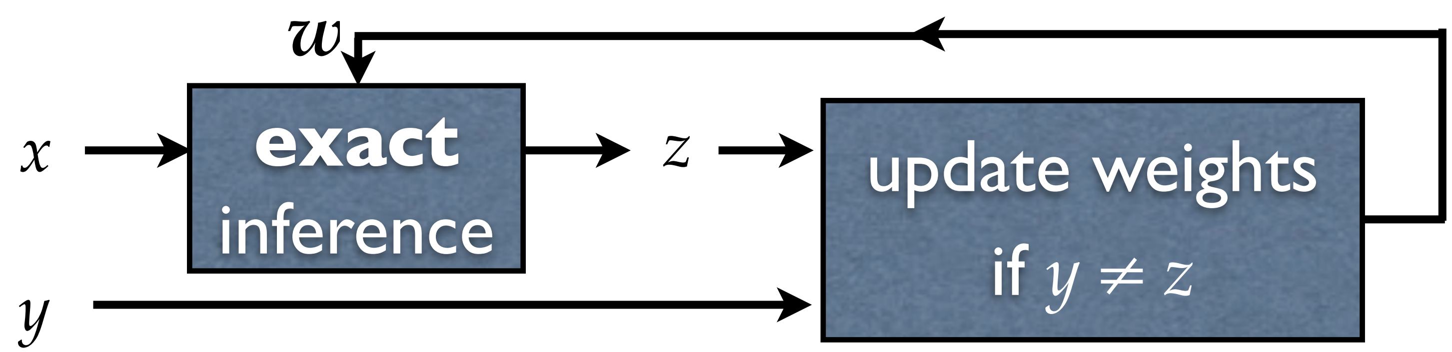

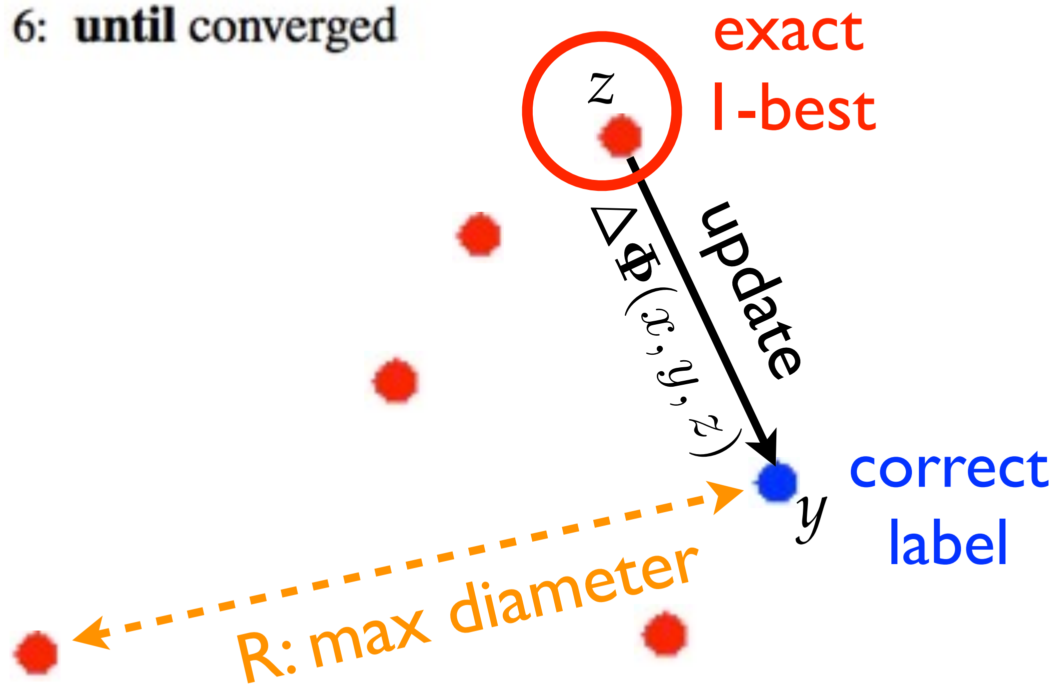

perceptron update:

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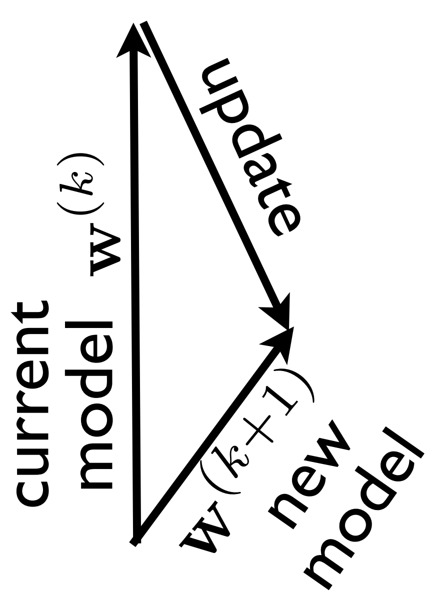
$\leq R^2$

diameter



Geometry of Convergence Proof pt 2

```
repeat
    for each example (x, y) in D do
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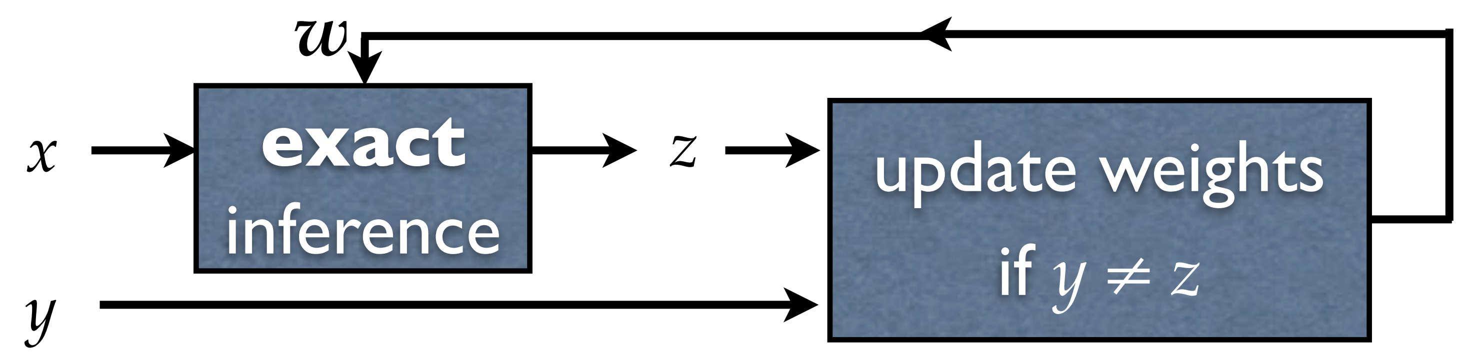

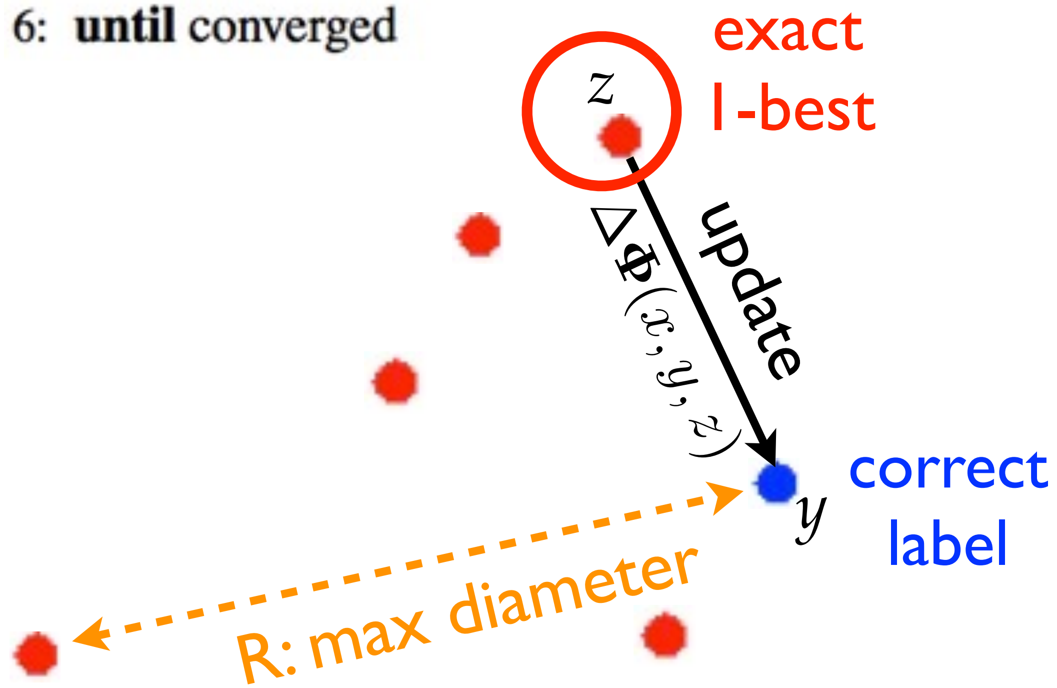

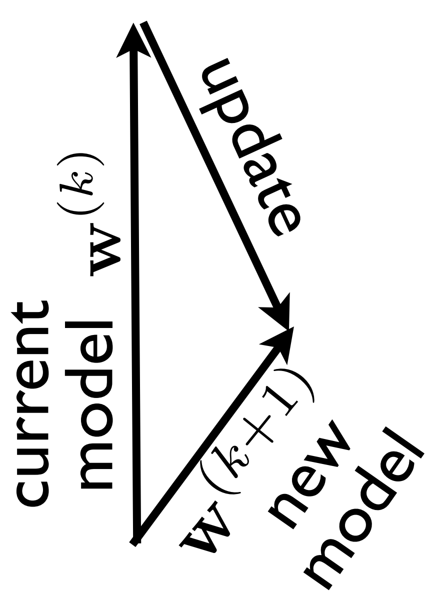

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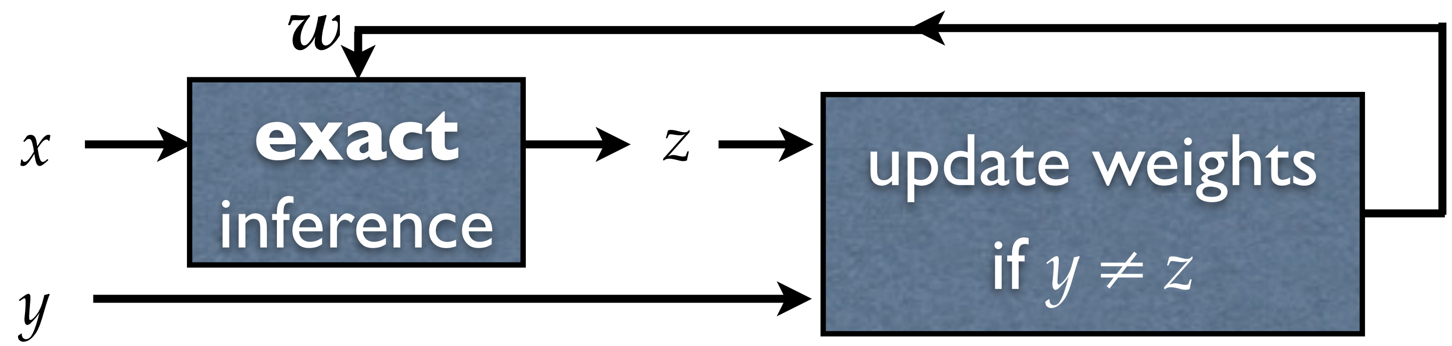
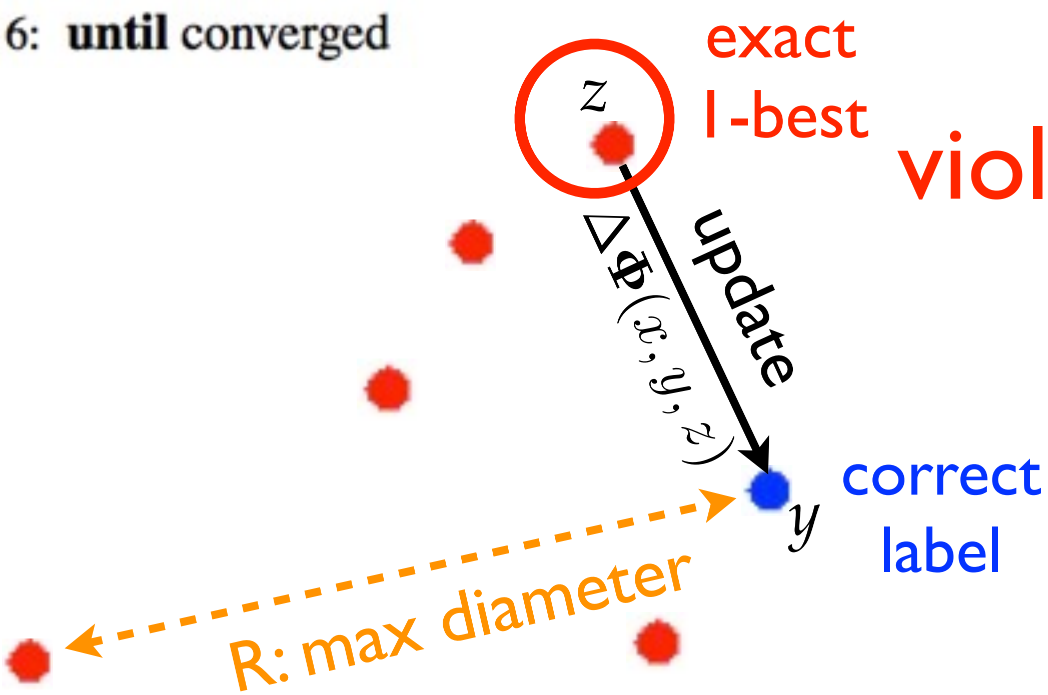
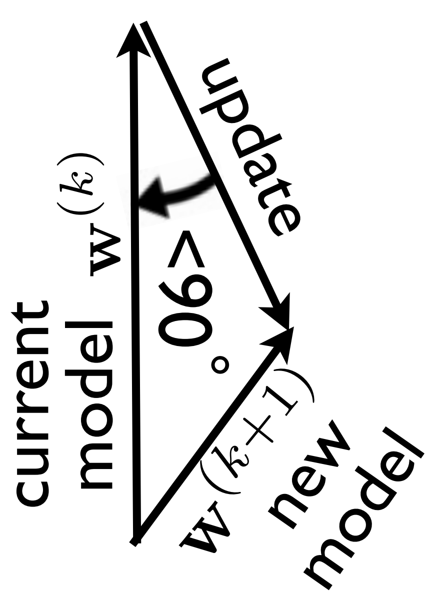




violation: incorrect label scored higher



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≤ 0 violation

Geometry of Convergence Proof pt 2

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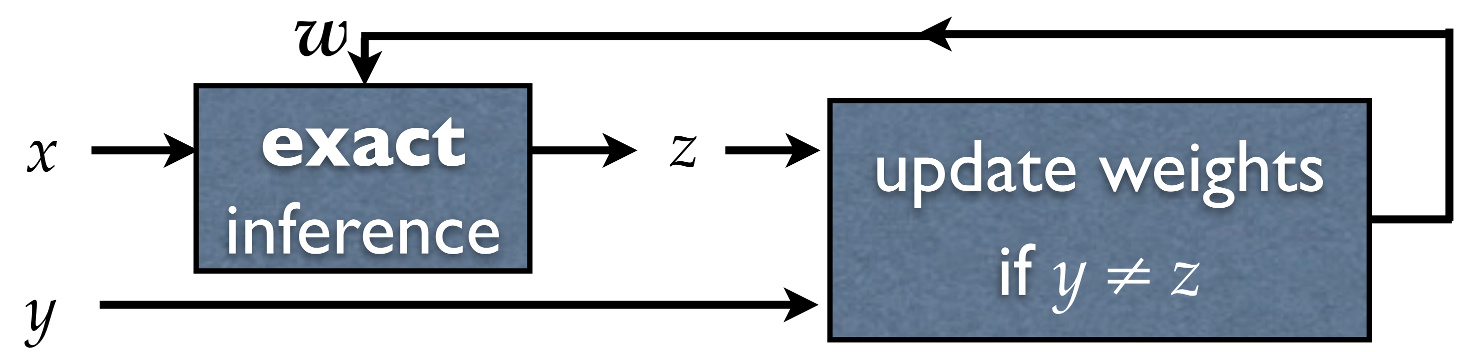

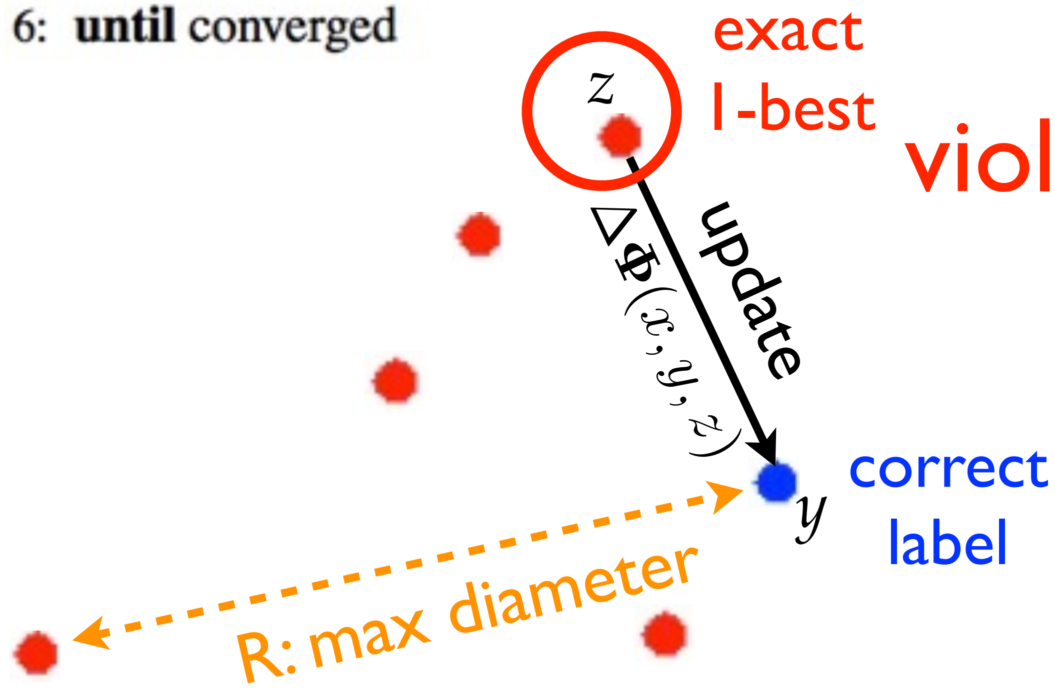

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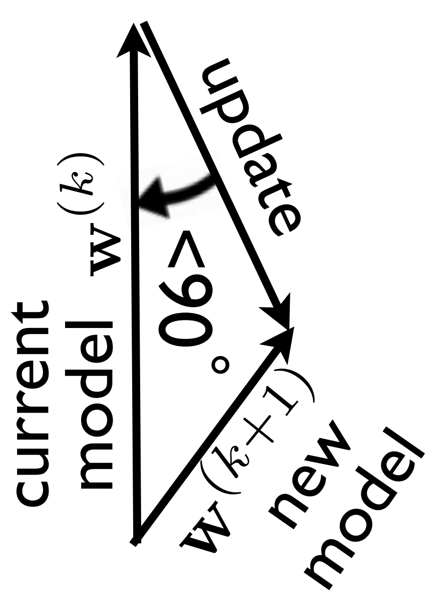

by induction: $\|\mathbf{w}^{(k+1)}\|^2 \leq kR^2$ (part 2: upperbound)

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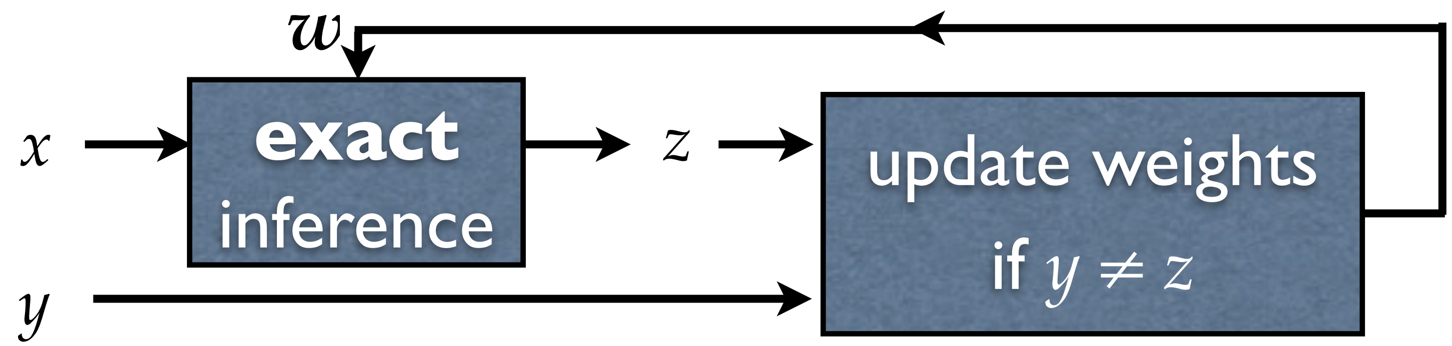

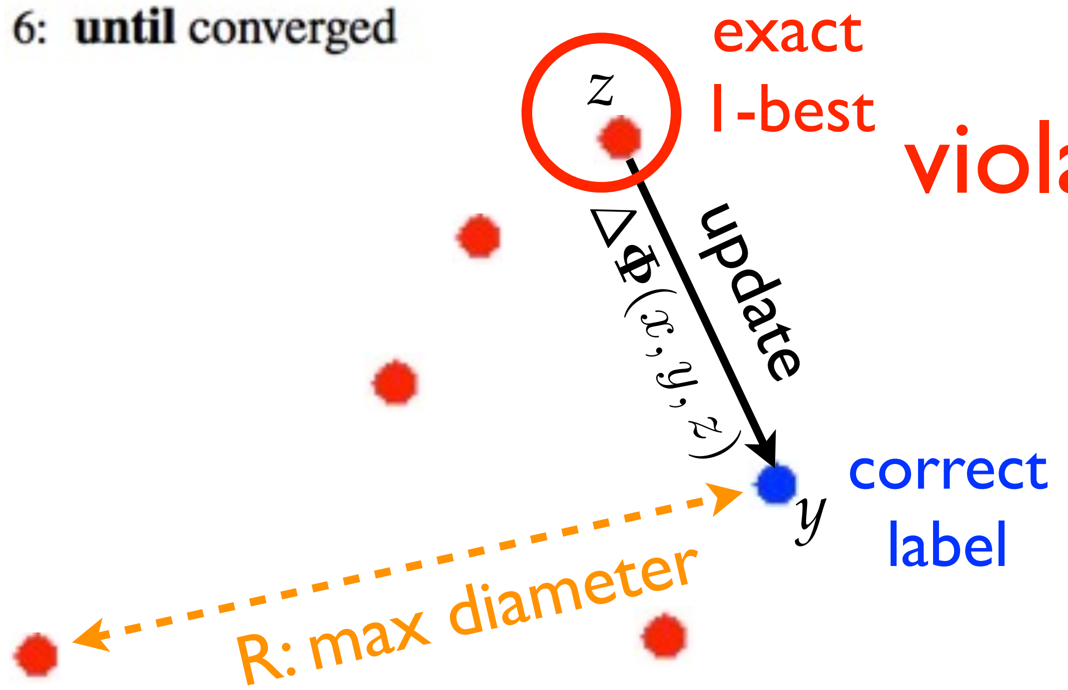

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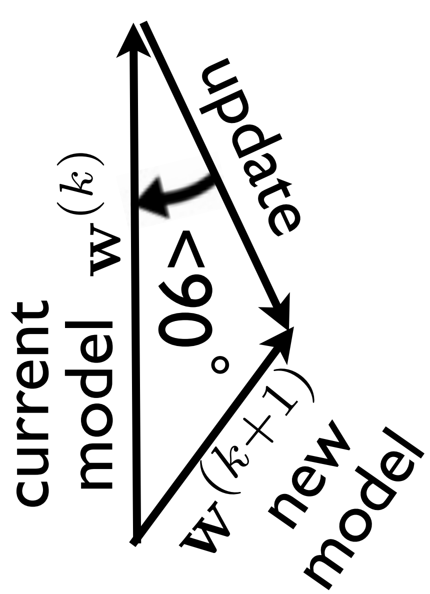
$\|\Delta\mathbf{\Phi}(x, y, z)\|^2 \leq R^2$ (diameter)

$2\,\mathbf{w}^{(k)} \cdot \Delta\mathbf{\Phi}(x, y, z) \leq 0$ (violation)



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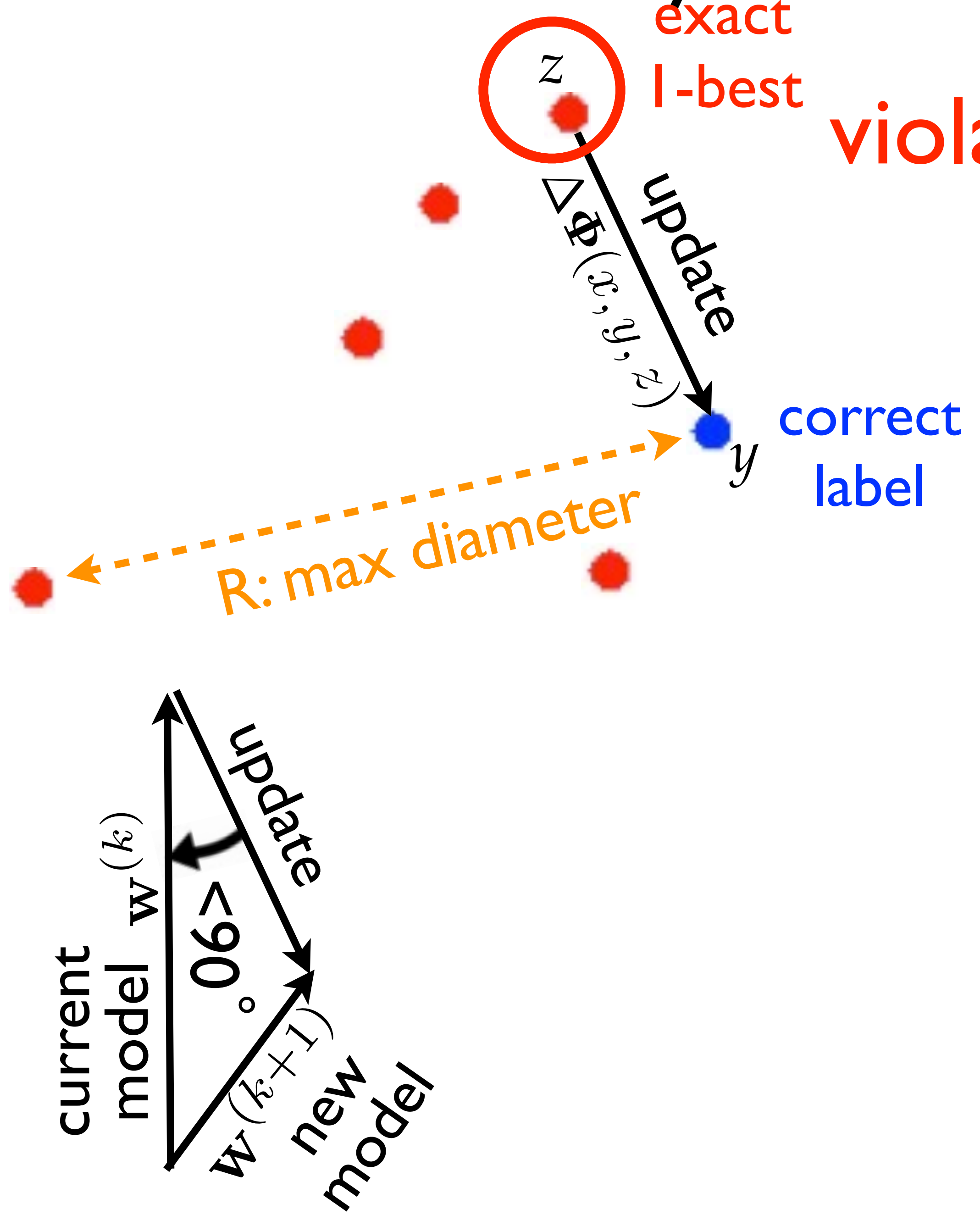
parts 1+2 => update bounds: $k \leq R^2/\delta^2$

Violation is All we need!

- exact search is **not** really required by the proof
  - rather, it is only used to ensure violation!



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the proof only uses 3 facts:

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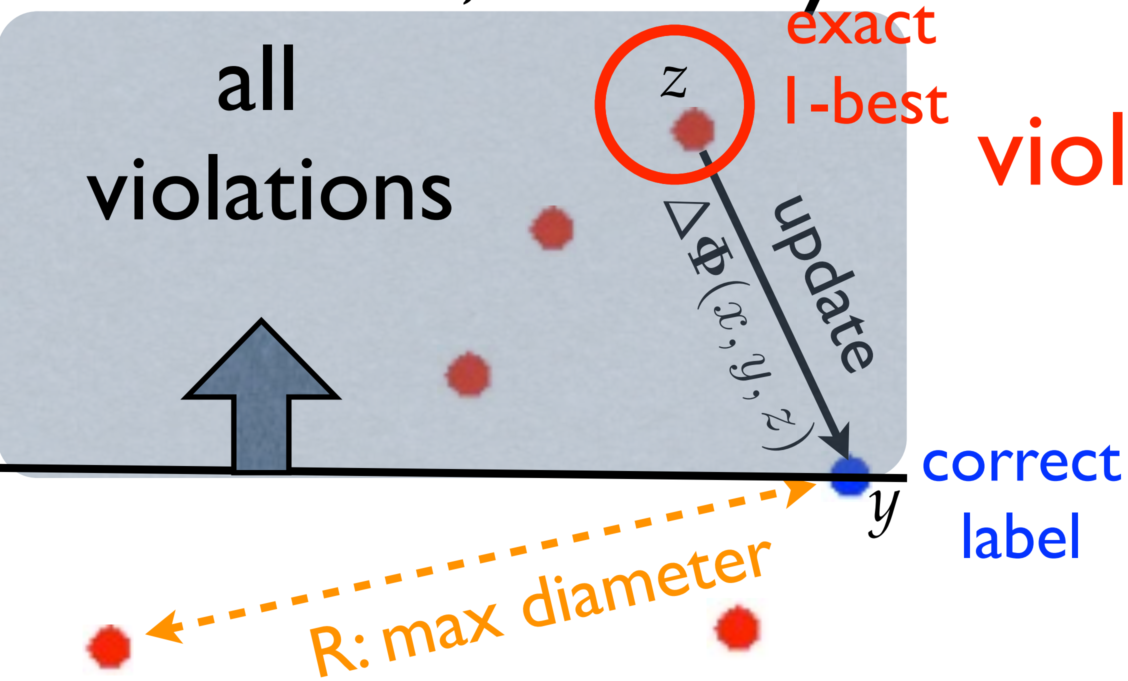

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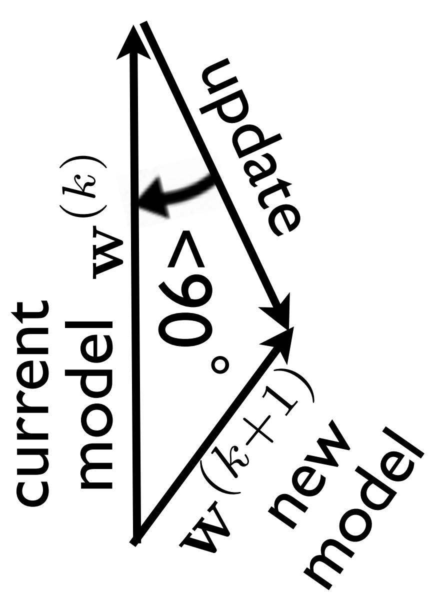

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Violation-Fixing Perceptron

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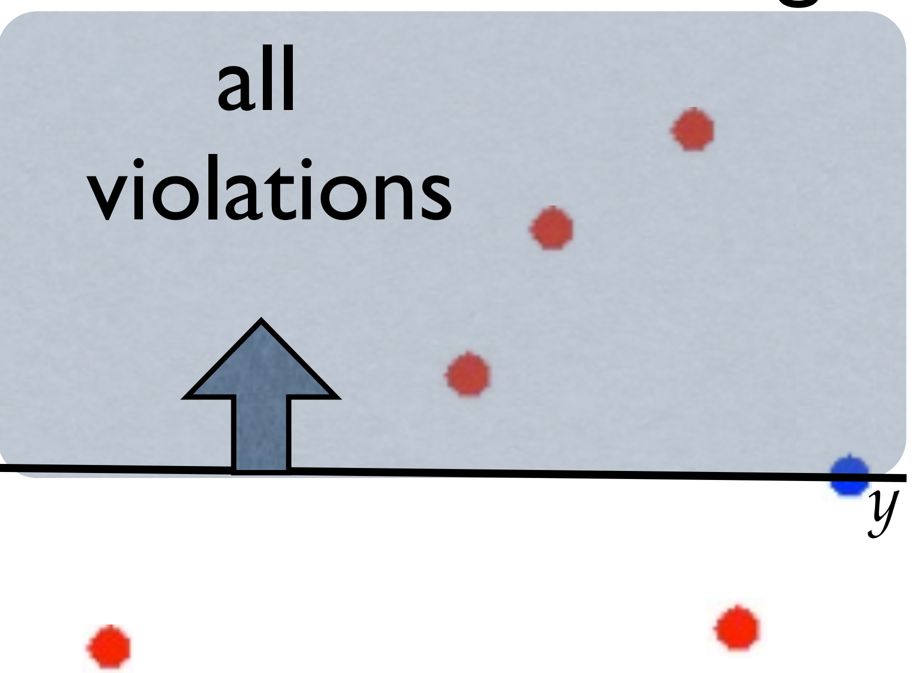
  - violation is good b/c we can at least fix a mistake



same mistake bound as before!

```
repeat
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        (x, y', z) = FINDVIOLATION(x, y, w)
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until converged
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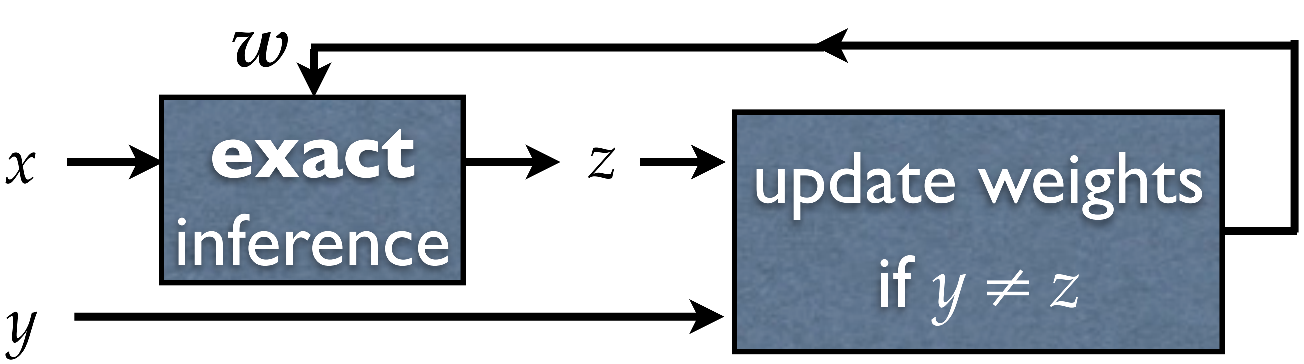
standard perceptron



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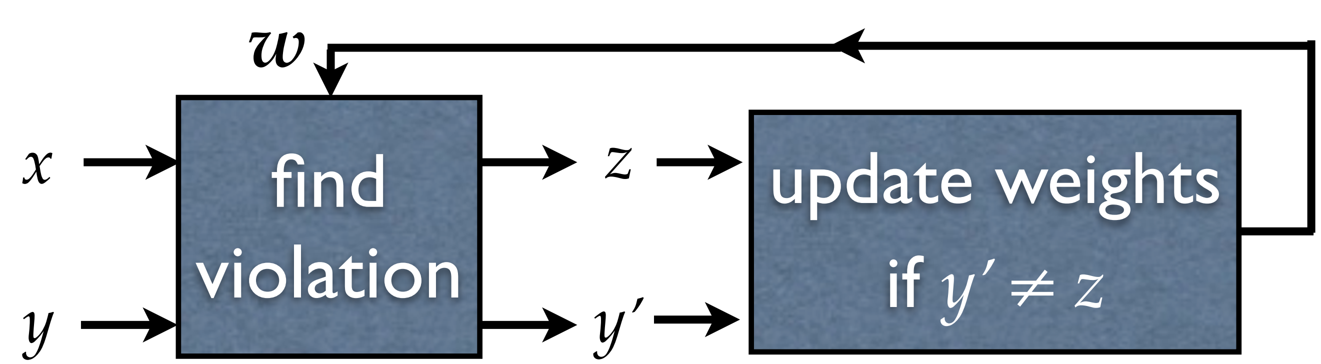

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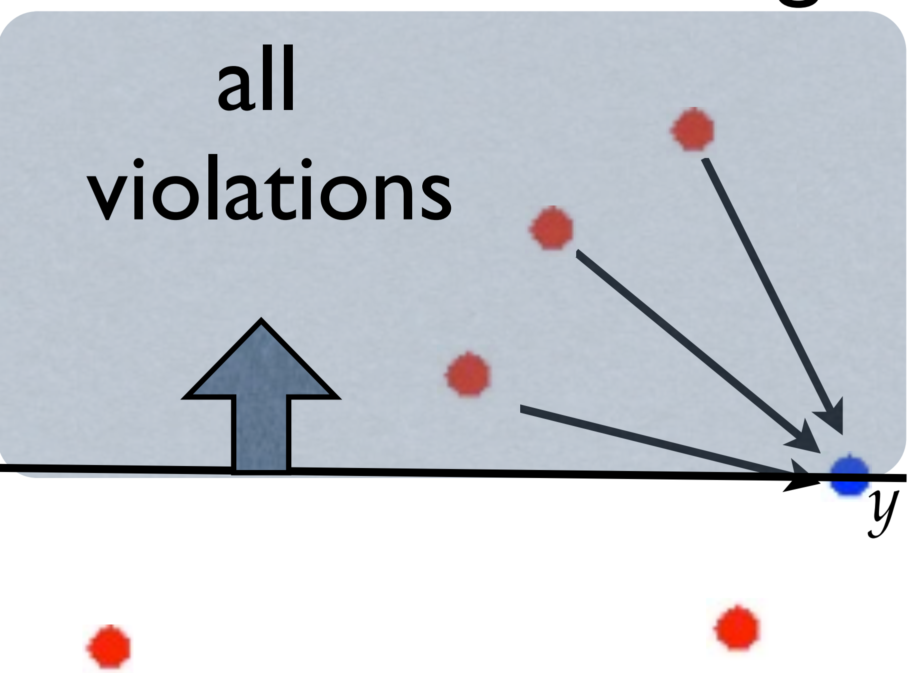

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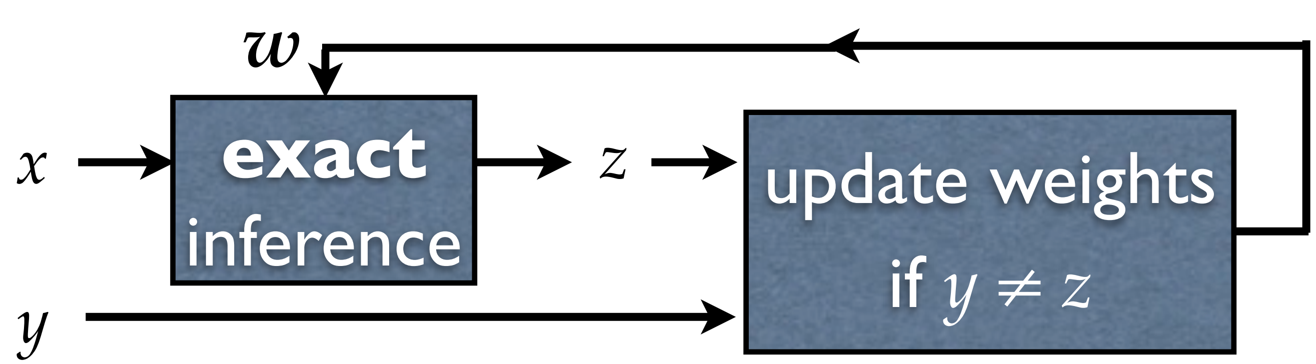

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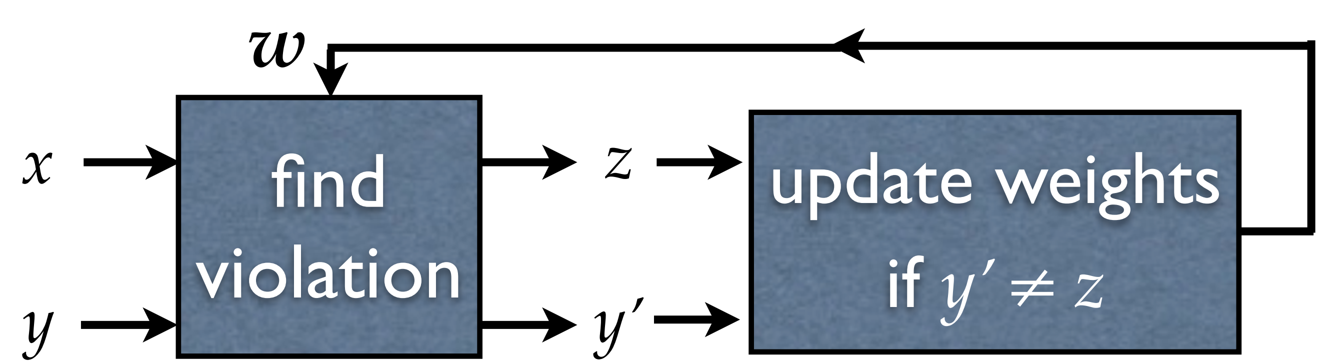

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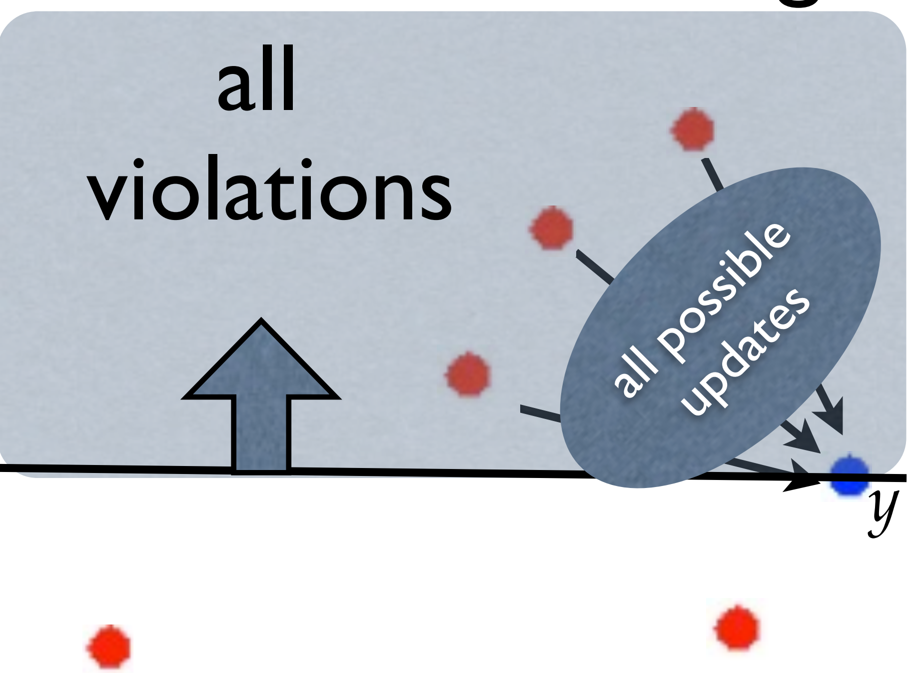

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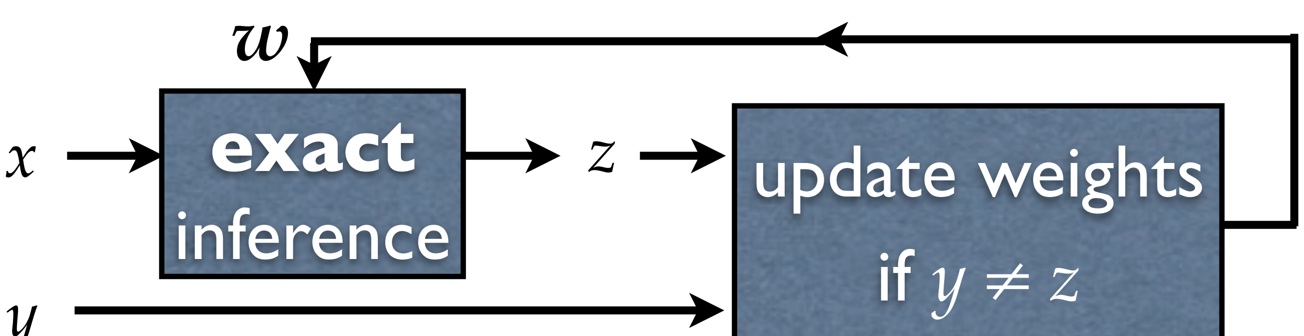

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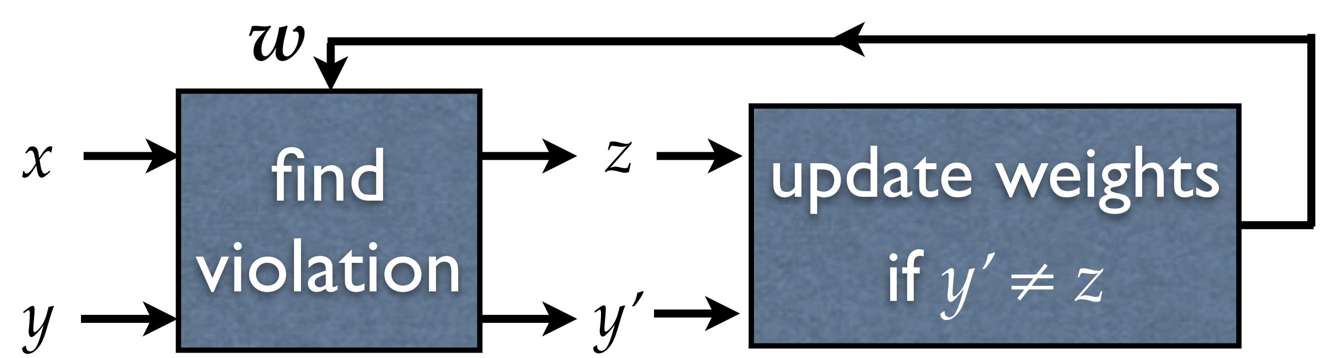
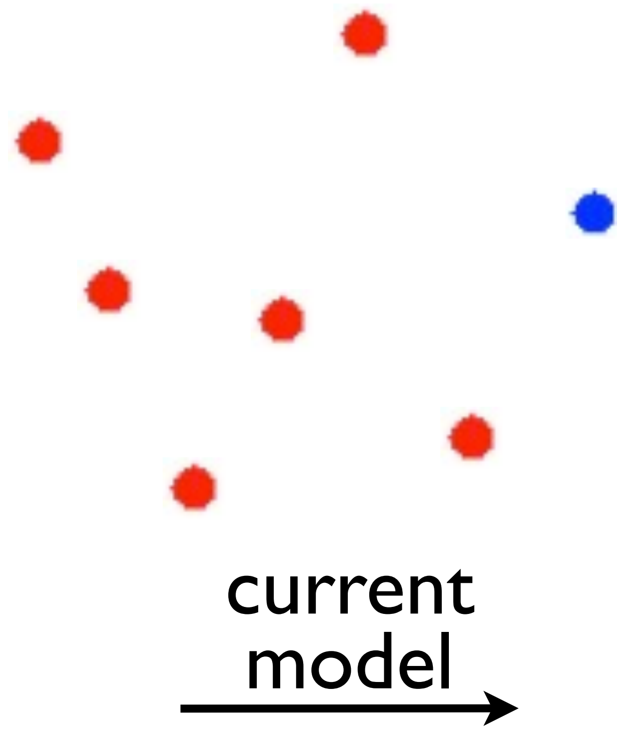


What if can’t guarantee violation



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- this is why perceptron doesn't work well w/ inexact search
  - because not every update is guaranteed to be a violation
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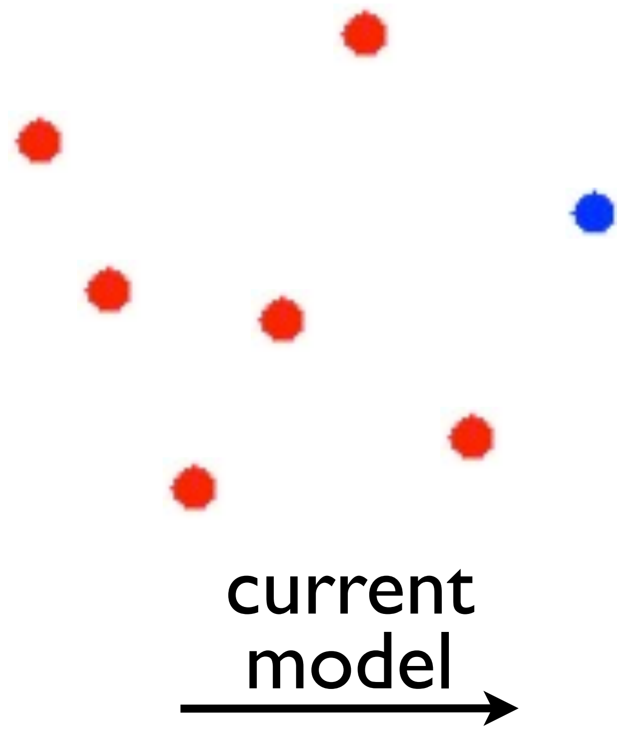
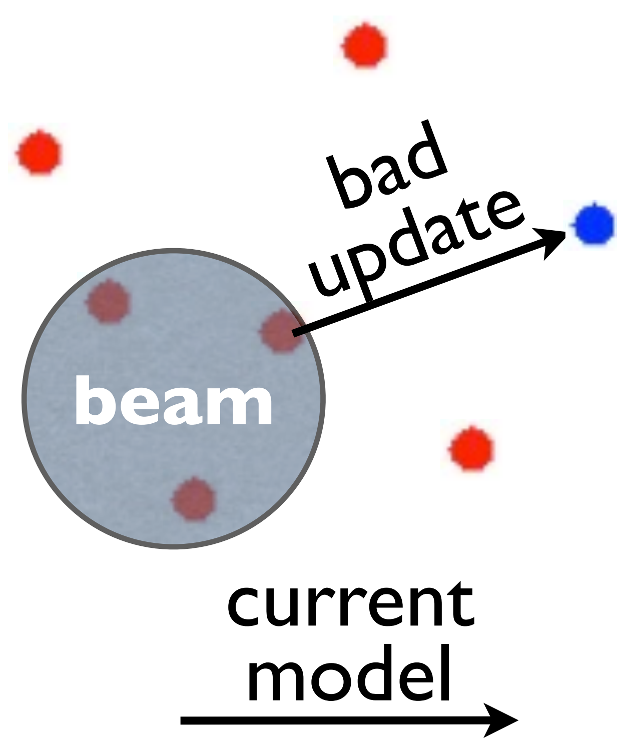
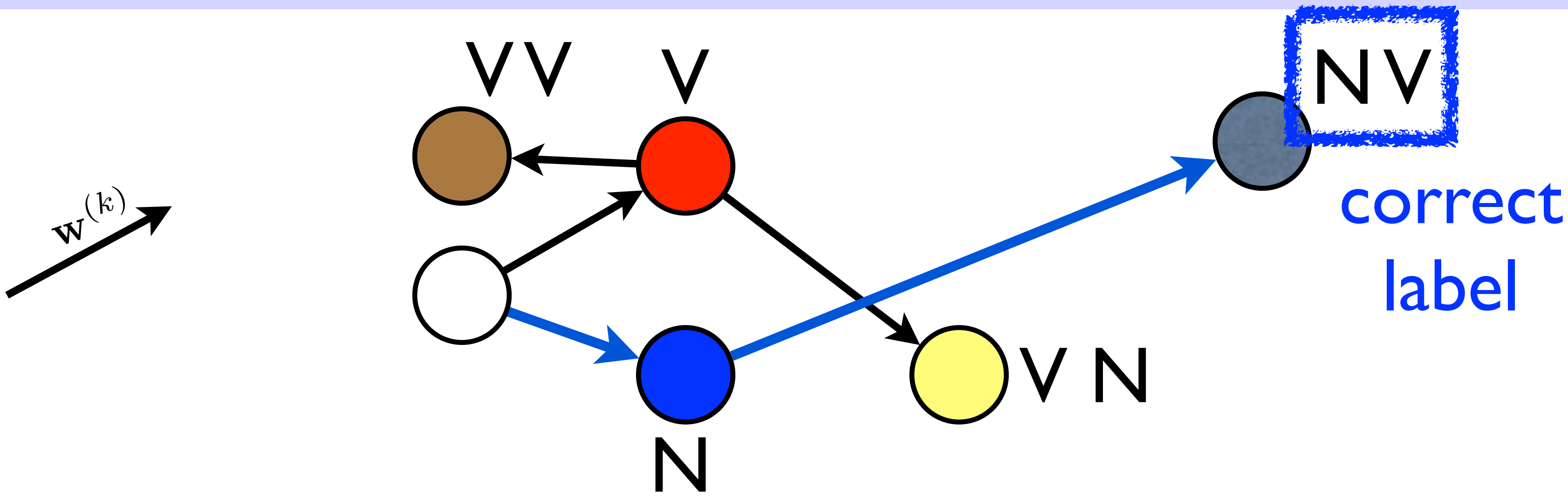


What if can't guarantee violation

- this is why perceptron doesn't work well w/ inexact search
  - because not every update is guaranteed to be a violation
  - thus the proof breaks; no convergence guarantee
- example: beam or greedy search
  - the model might prefer the correct label (if exact search)
  - but the search prunes it away
  - such a non-violation update is "bad" because it doesn't fix any mistake
  - the new model still misguides the search



Standard Update: No Guarantee



training example

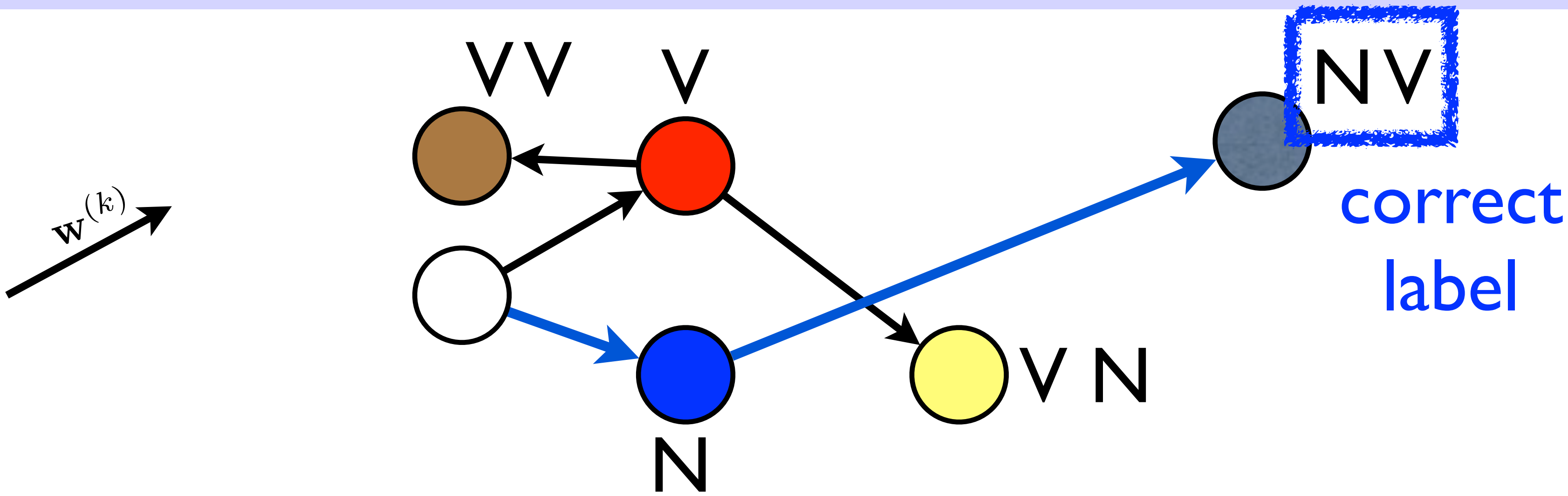
time flies

N V

output space

{N,V} x {N,V}

Standard Update: No Guarantee



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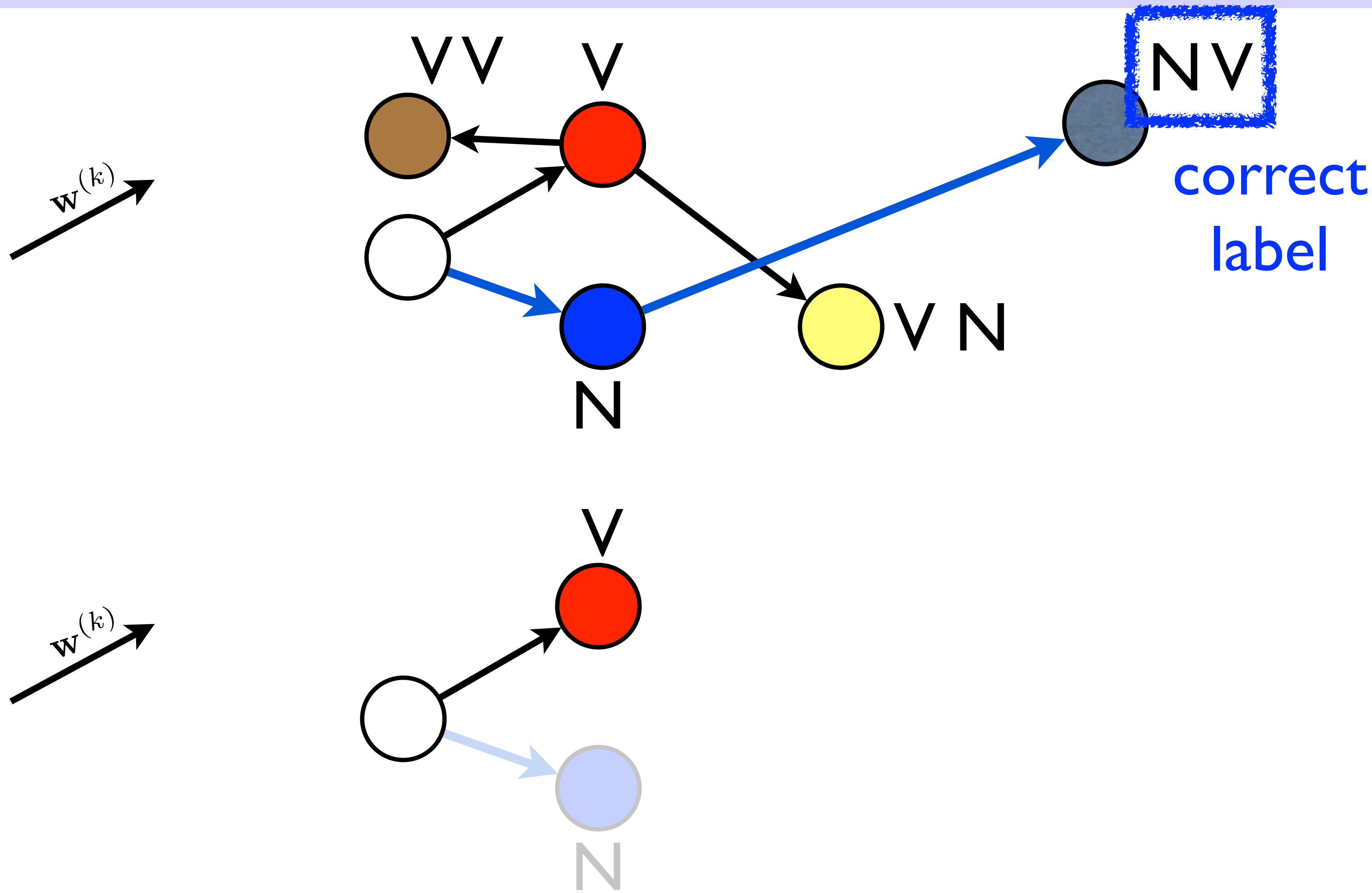

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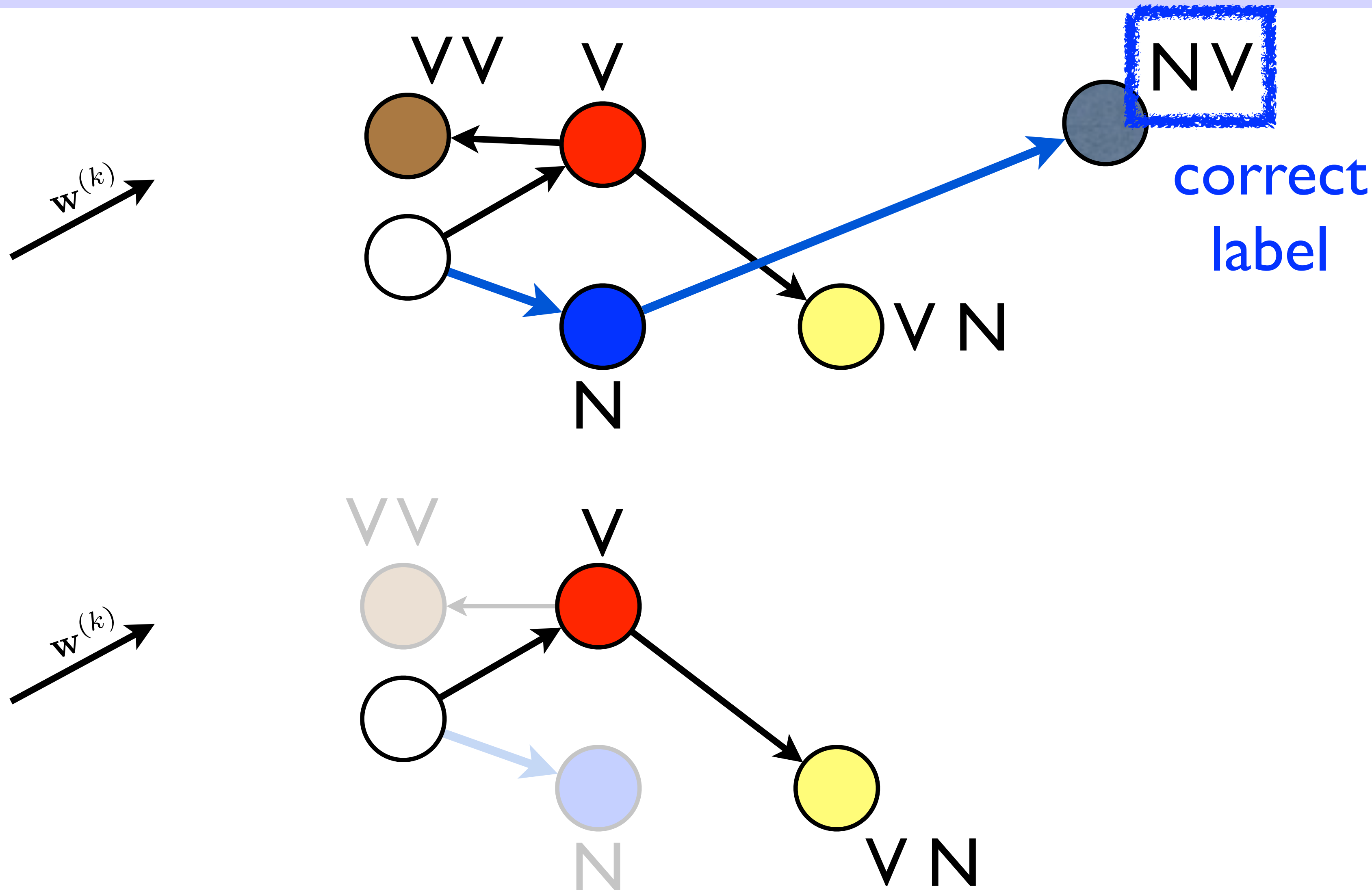

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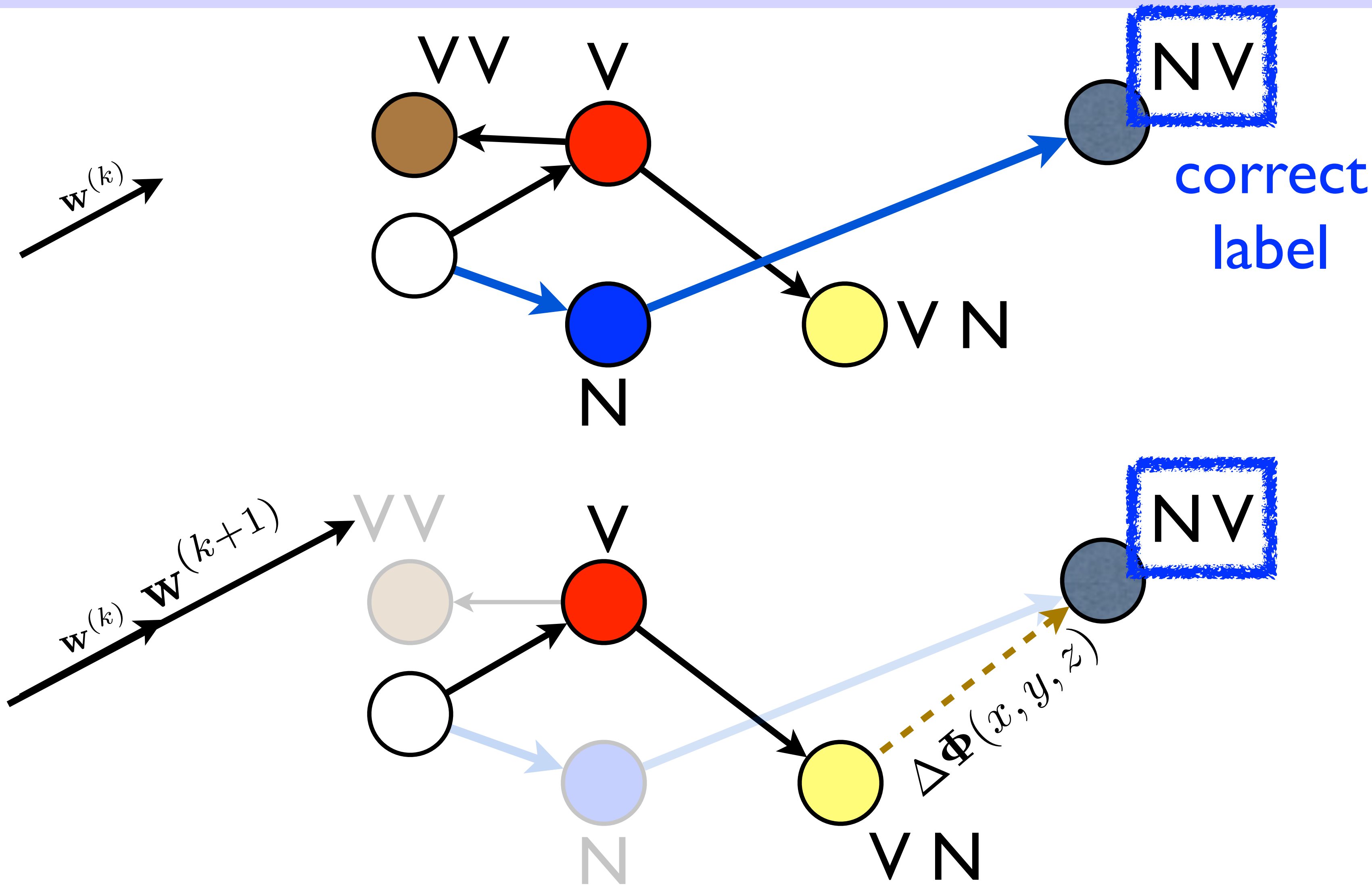

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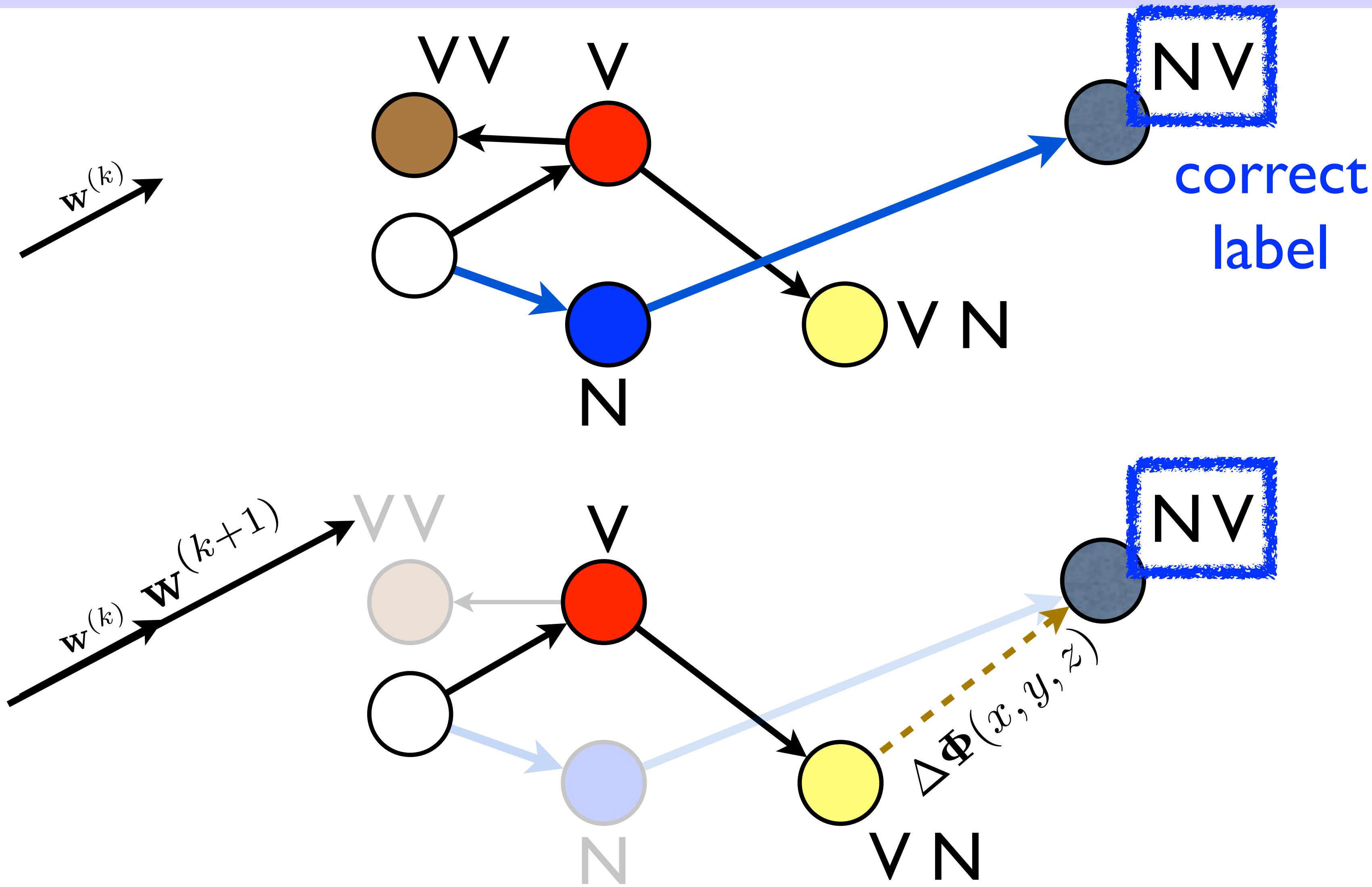

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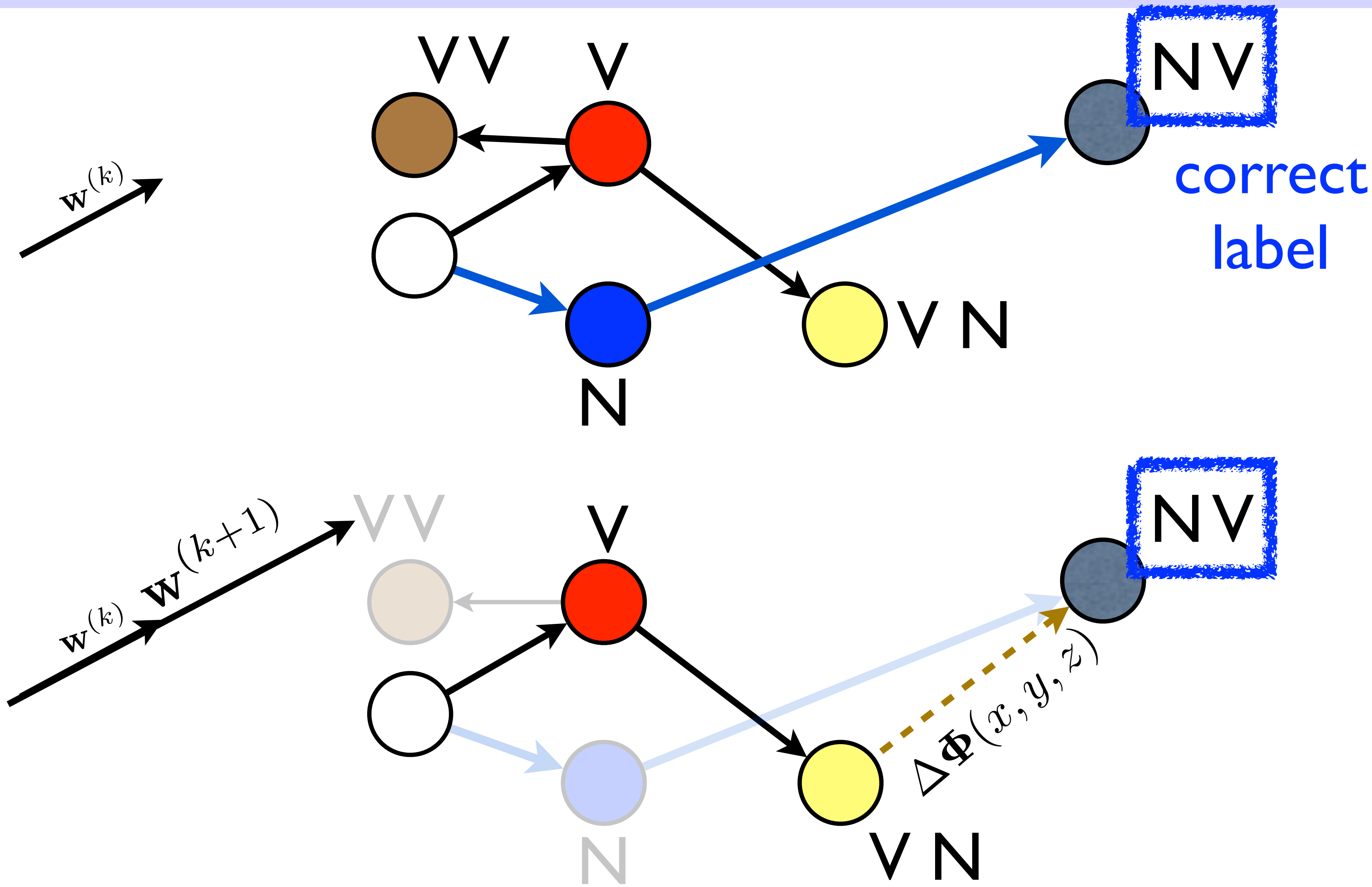
standard update doesn't converge b/c it doesn't guarantee violation

correct label scores higher.

non-violation: bad update!

Early Update: Guarantees Violation



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√	√	···	√	×	
←		update		→	skip →

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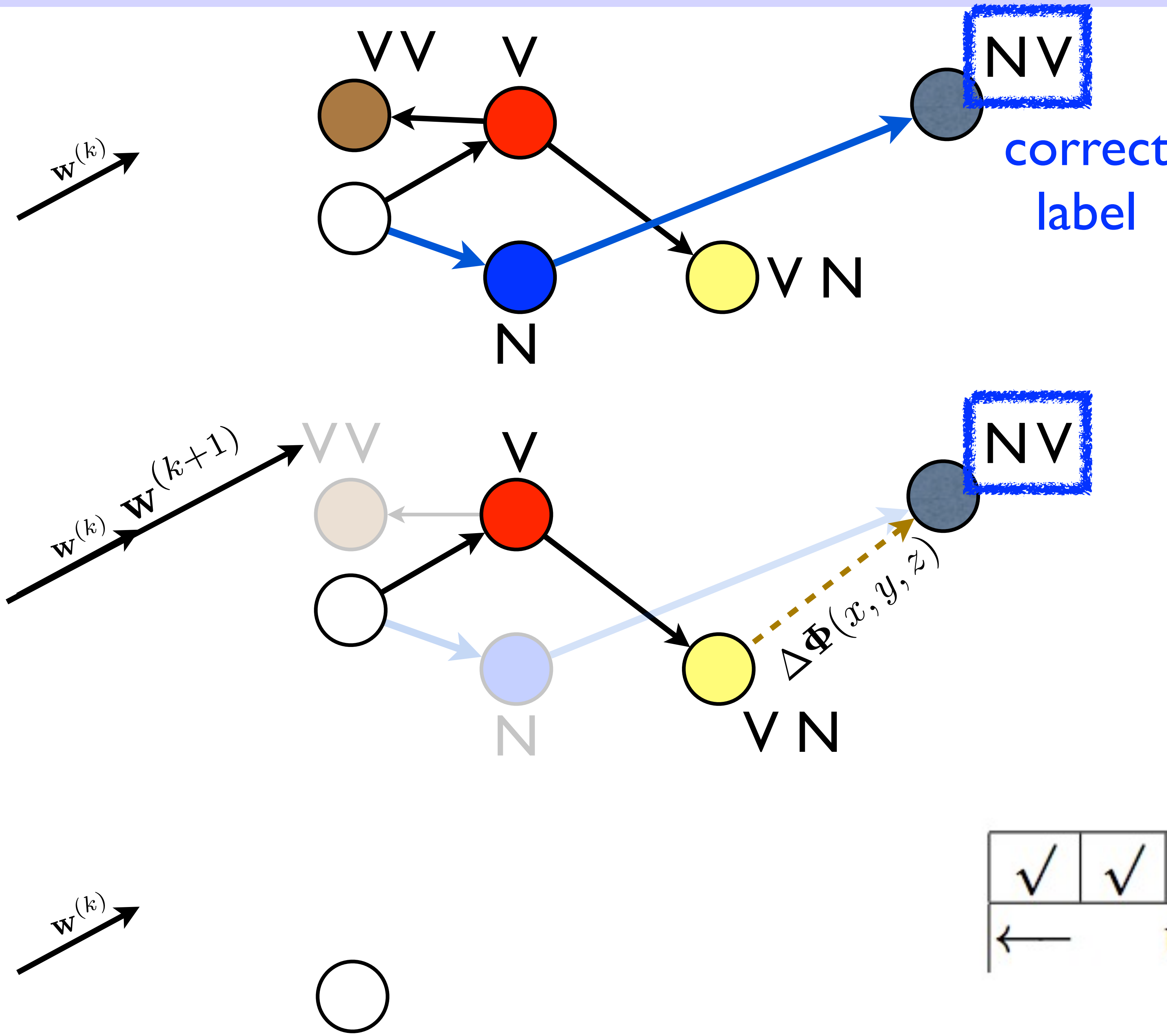

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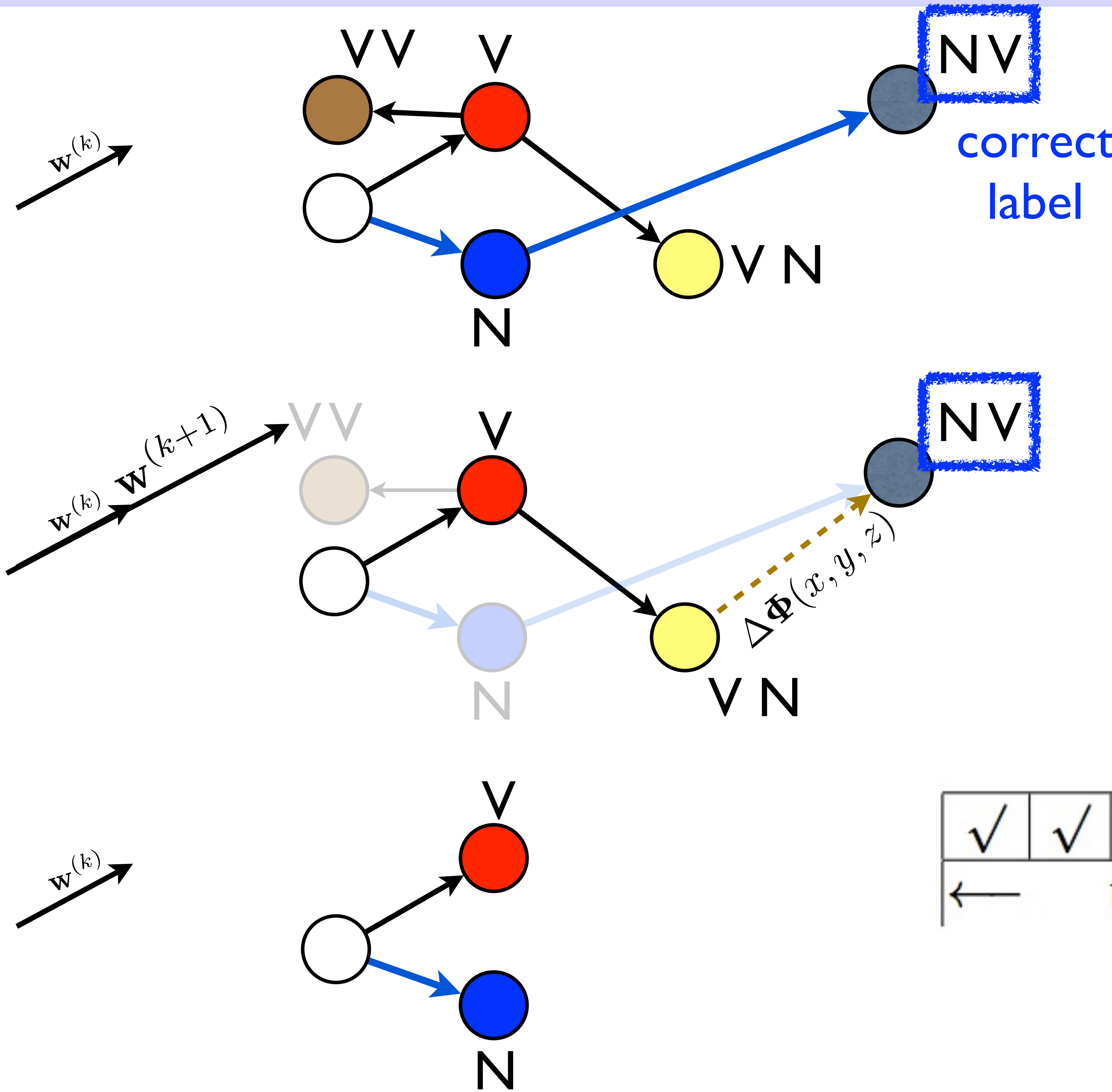

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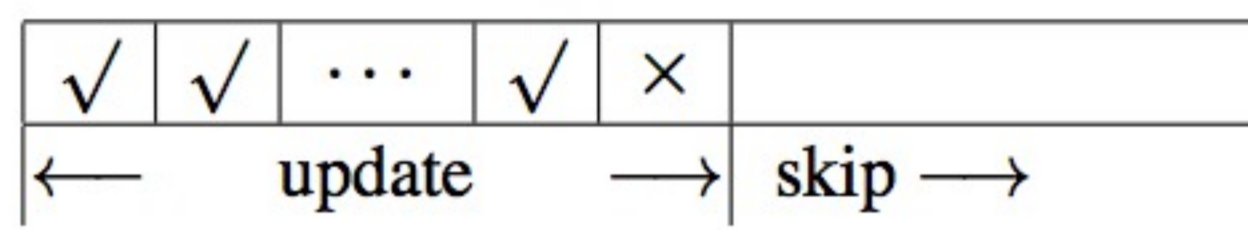

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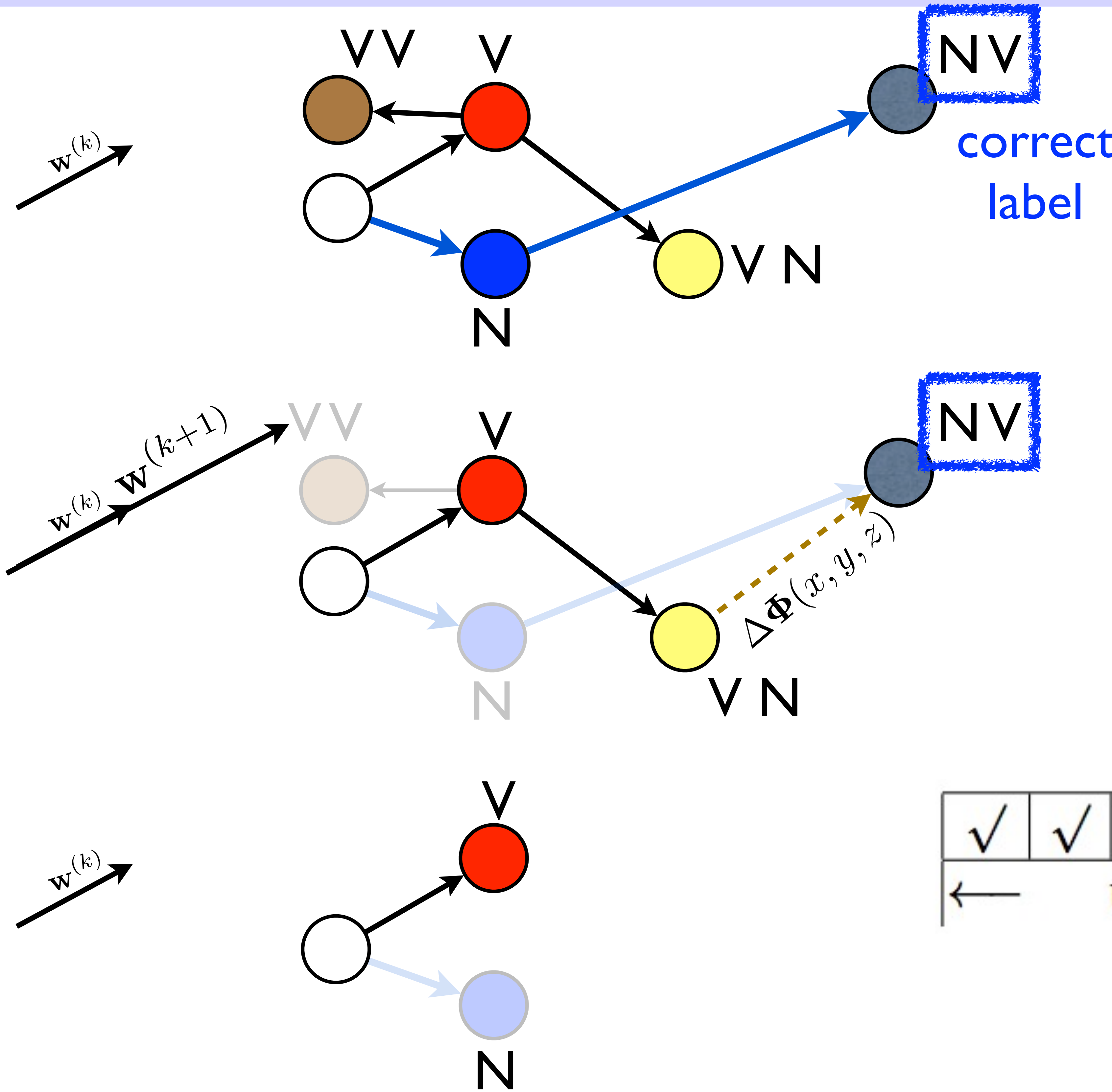

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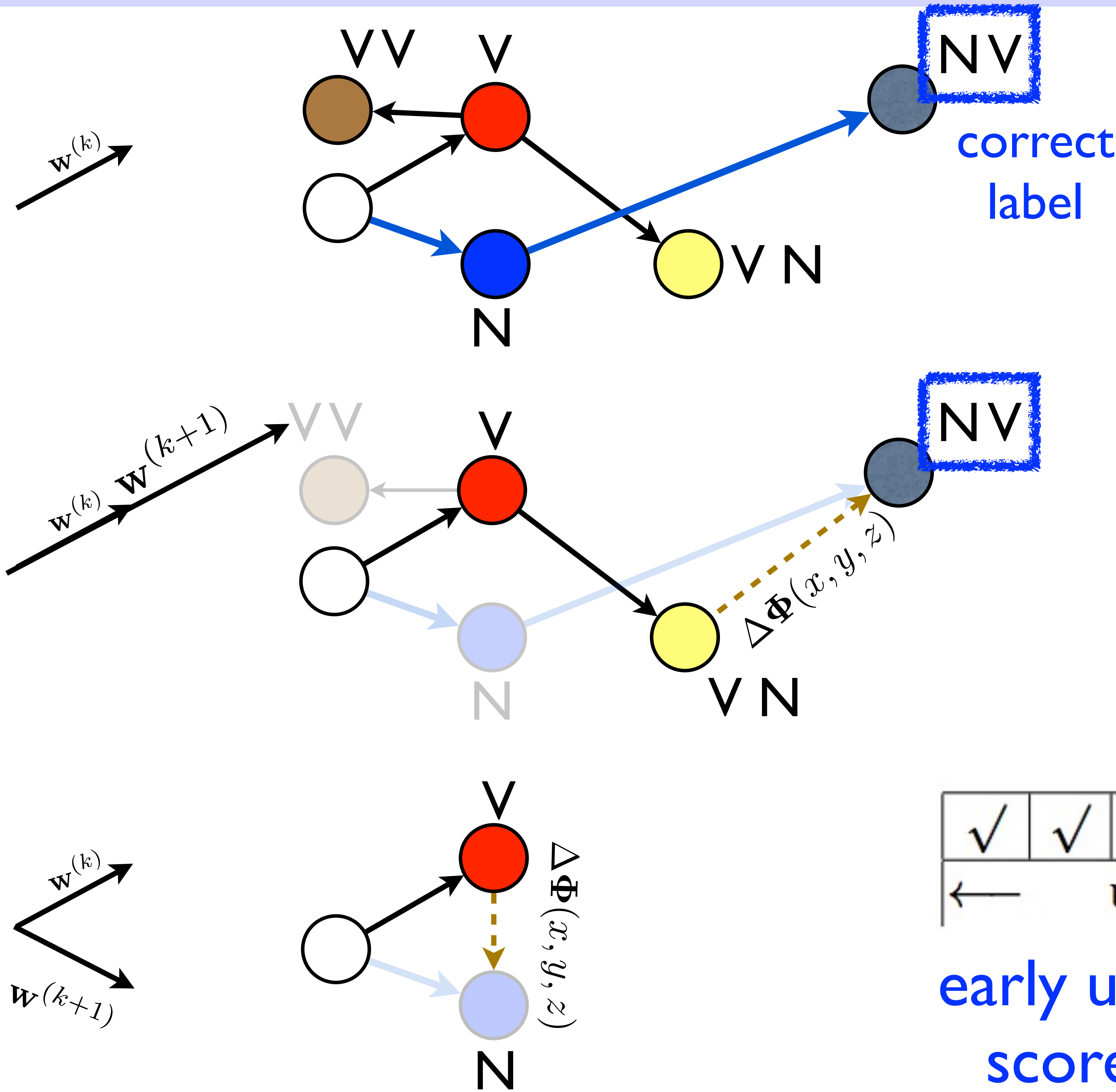

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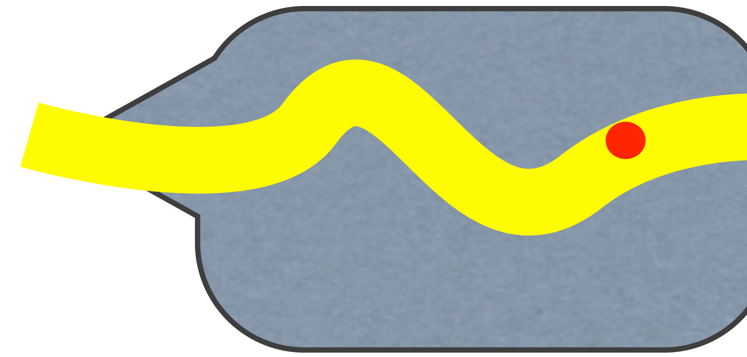
√	√	···	√	×	
⟵	update			⟶	skip ⟶

early update: incorrect prefix scores higher: a violation!

Early Update: from Greedy to Beam

- beam search is a generalization of greedy (where b=1)
  - at each stage we keep top b hypothesis
  - widely used: tagging, parsing, translation...



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standard update
(no guarantee!)

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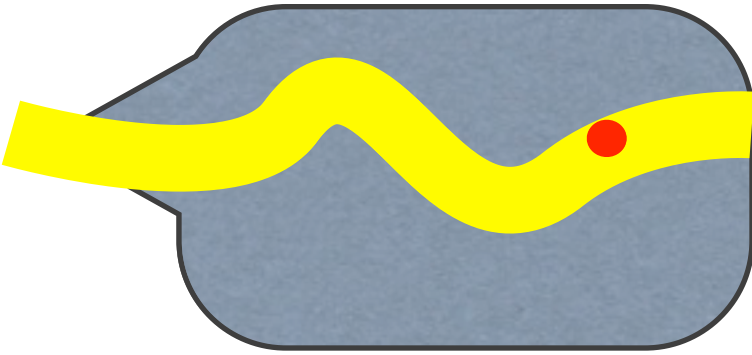

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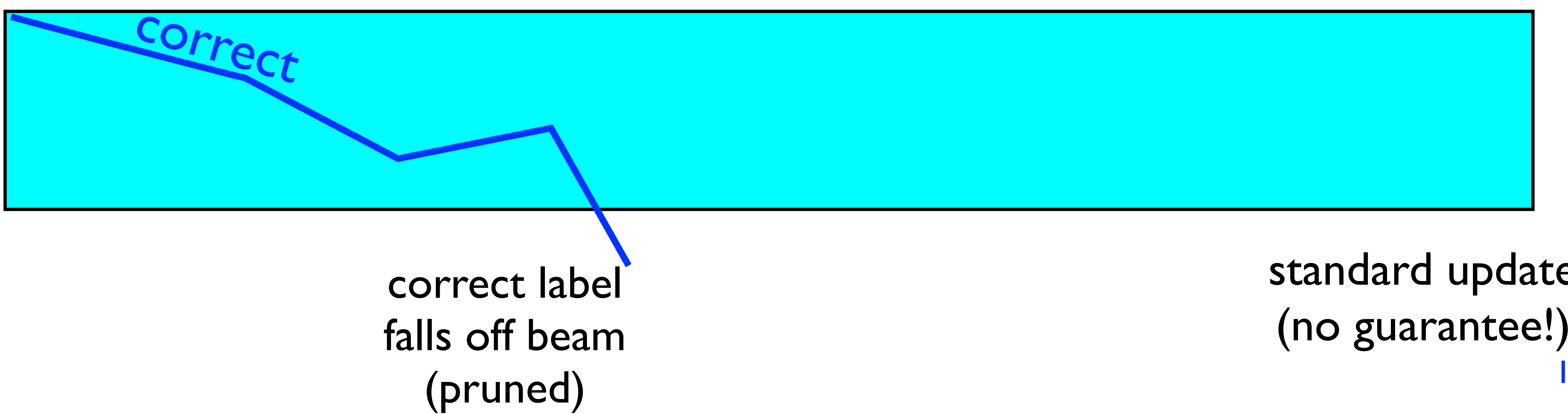

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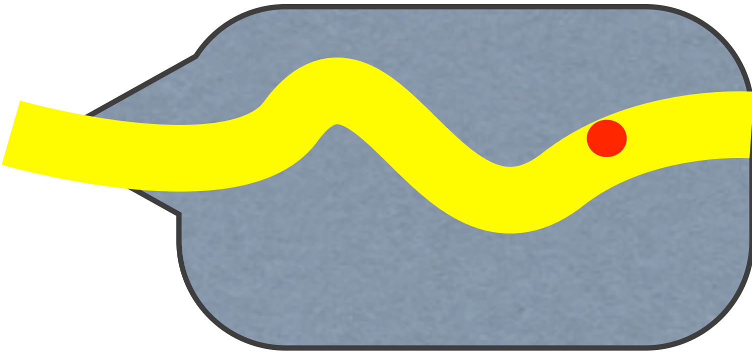

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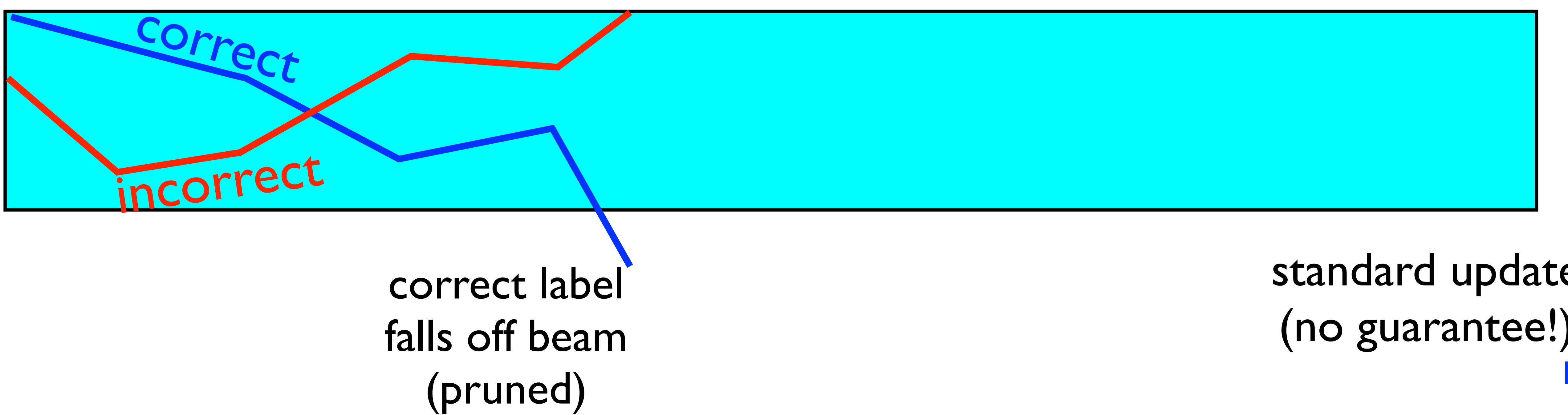

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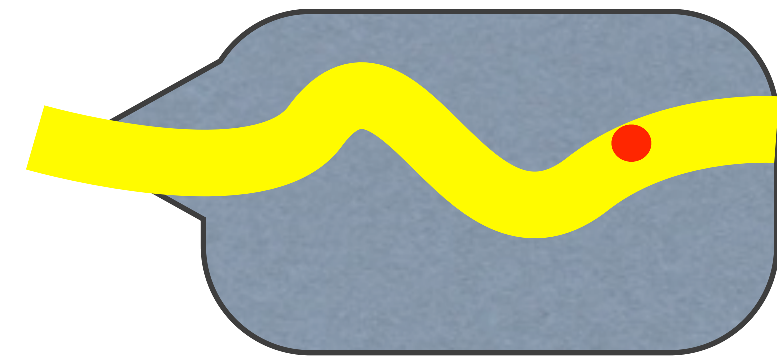

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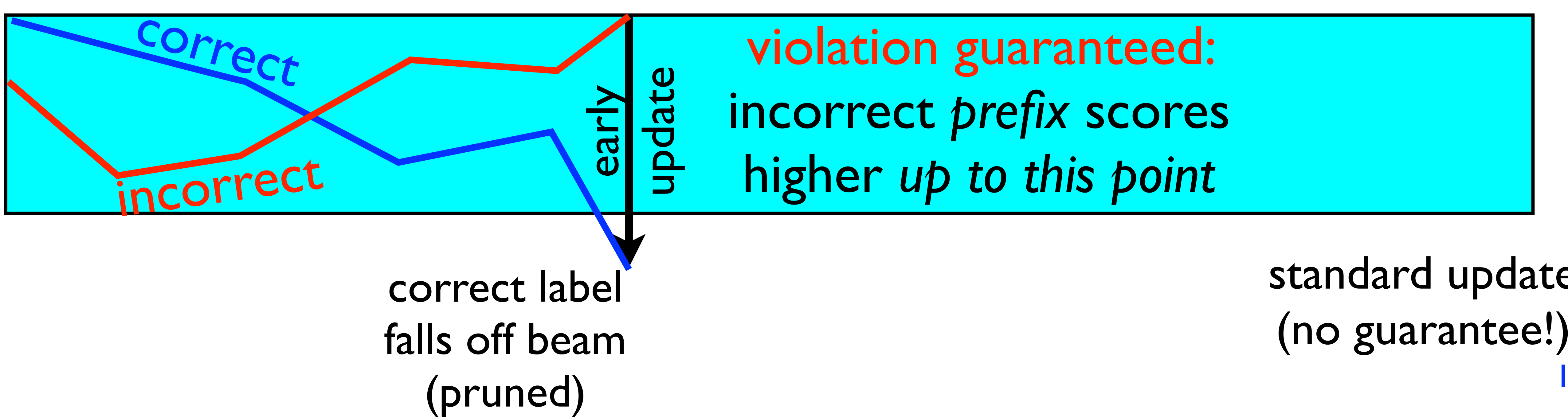
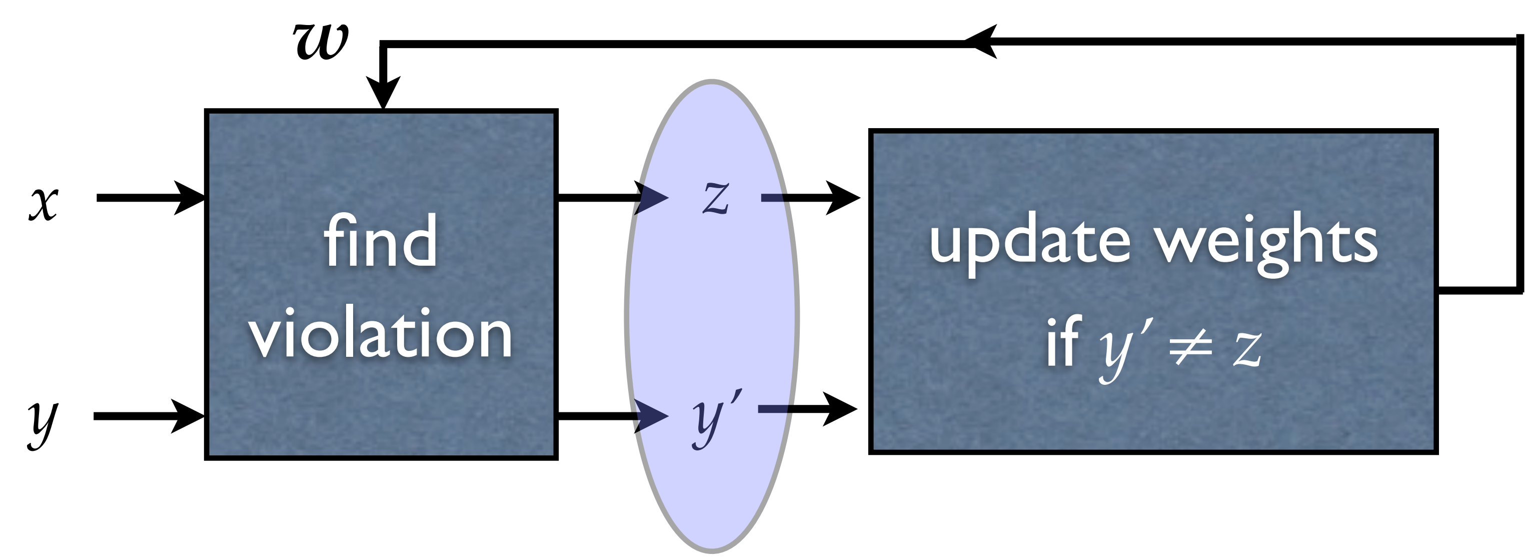
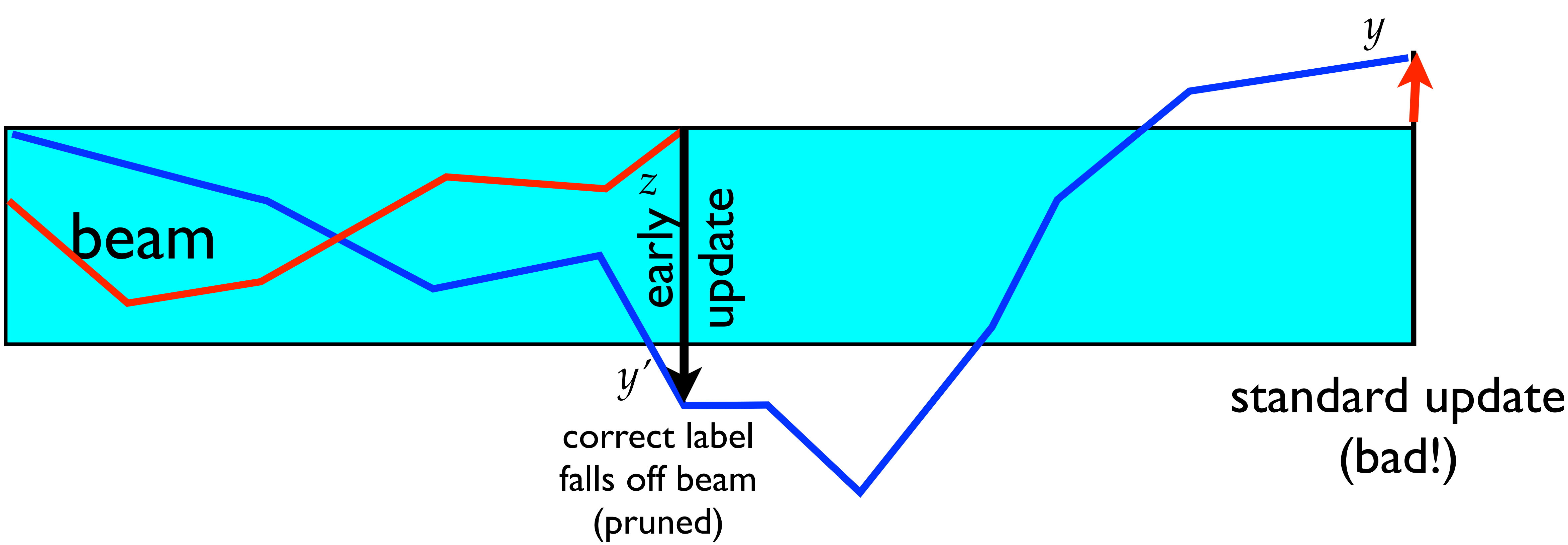


Early Update as Violation-Fixing



prefix violations

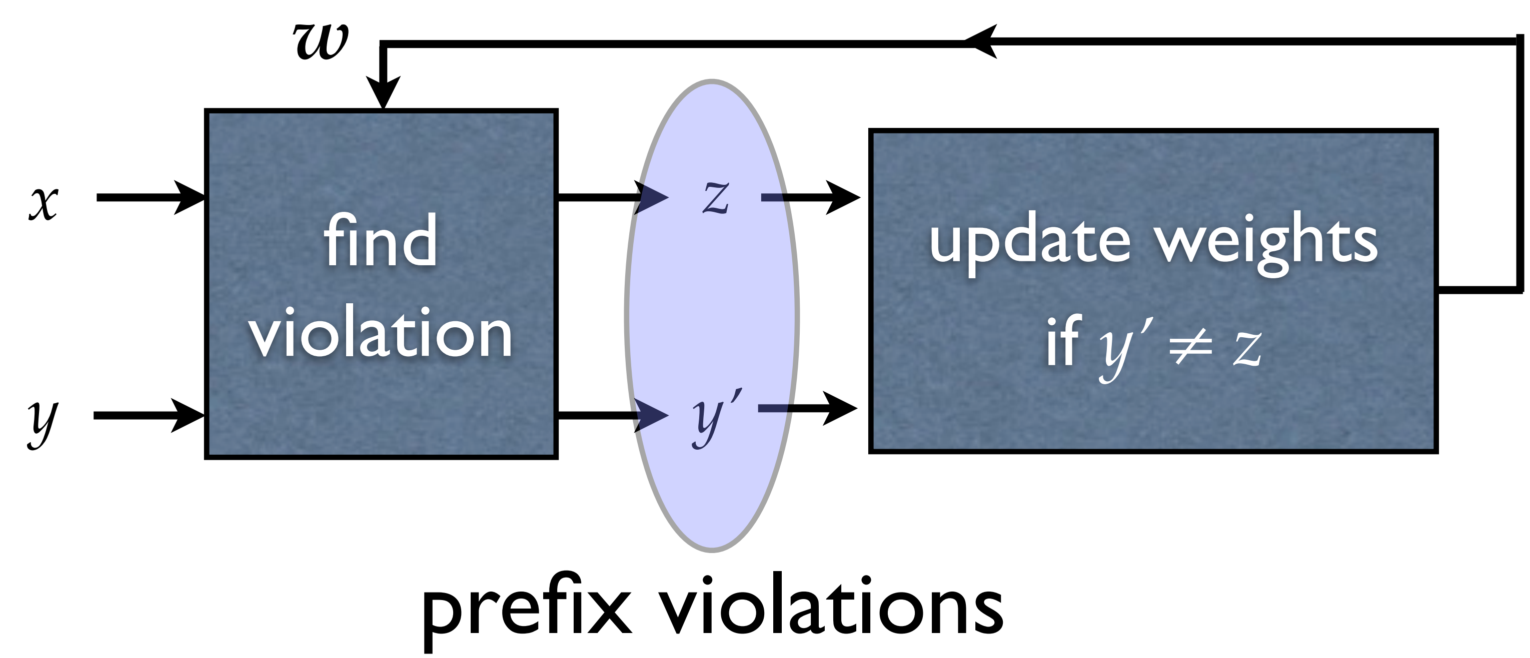


Early Update as Violation-Fixing

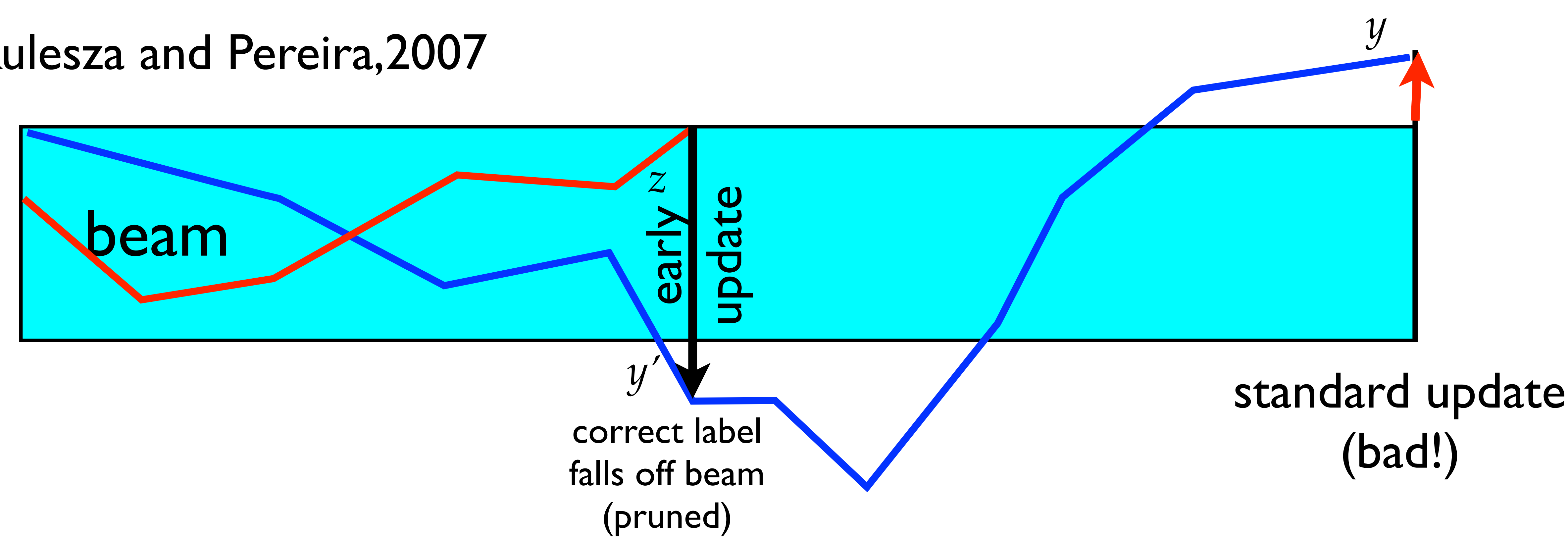
also new definition of "beam separability":

a correct prefix should score higher than *any* incorrect prefix of the same length

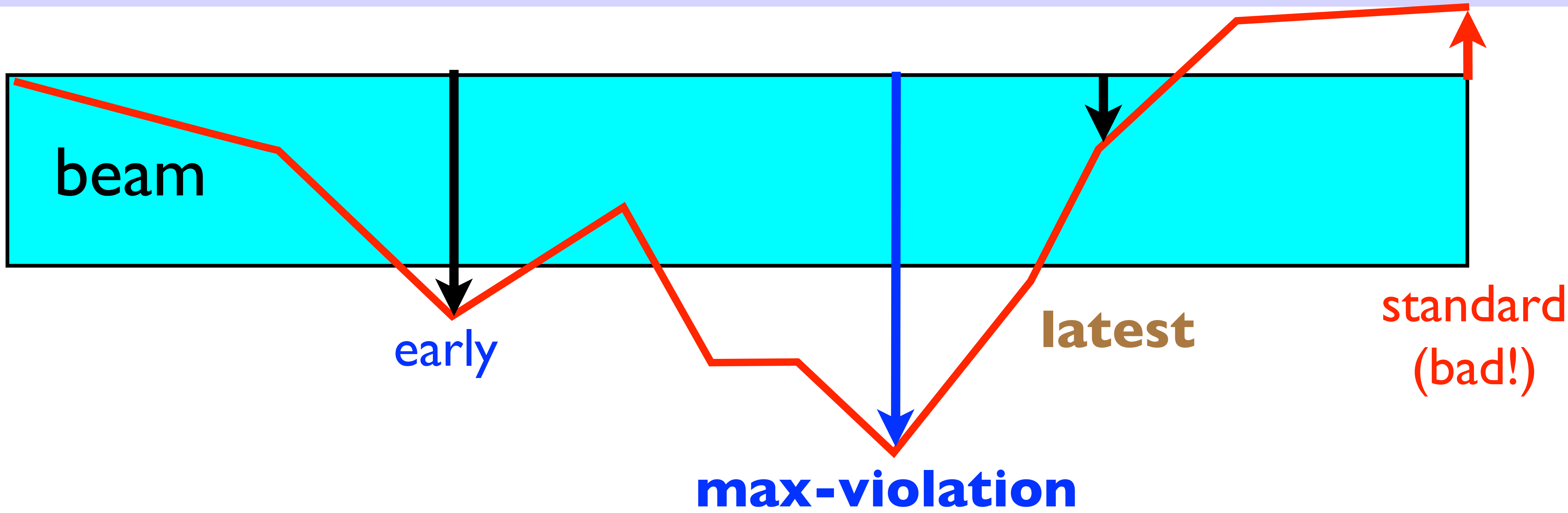
(maybe too strong)



cf. Kulesza and Pereira,2007



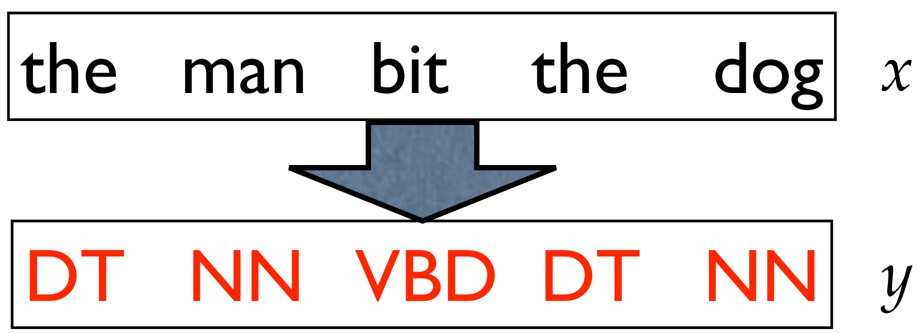
New Update Methods: max-violation, ...



- we now established a theory for early update (Collins/Roark)
- but it learns too slowly due to partial updates
- max-violation: use the prefix where violation is maximum
  - "worst-mistake" in the search space
- all these update methods are violation-fixing perceptrons

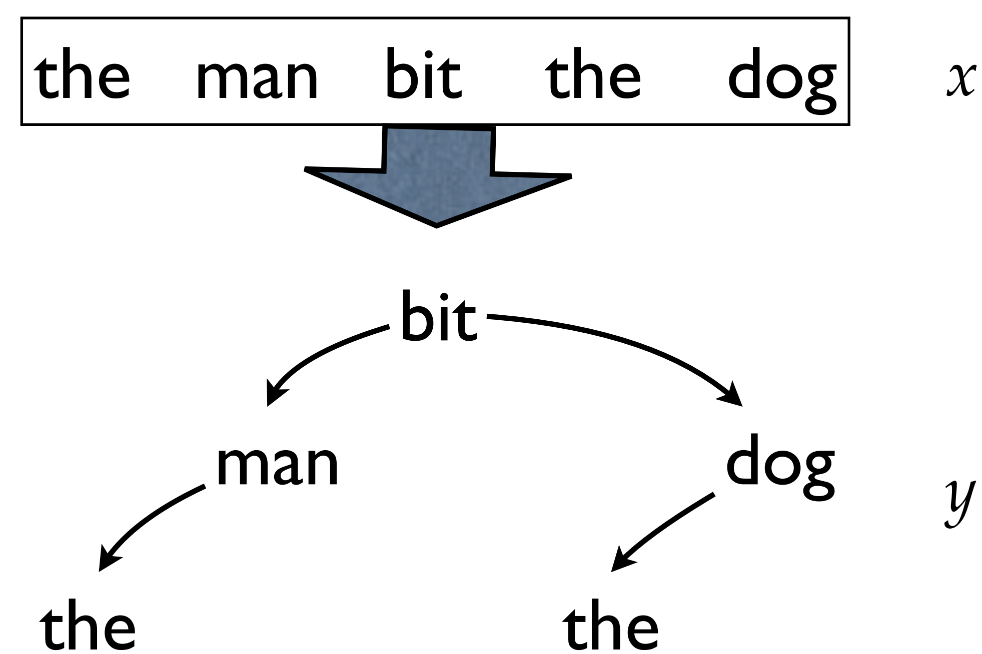
Experiments

trigram part-of-speech tagging



local features only,
exact search tractable
(proof of concept)

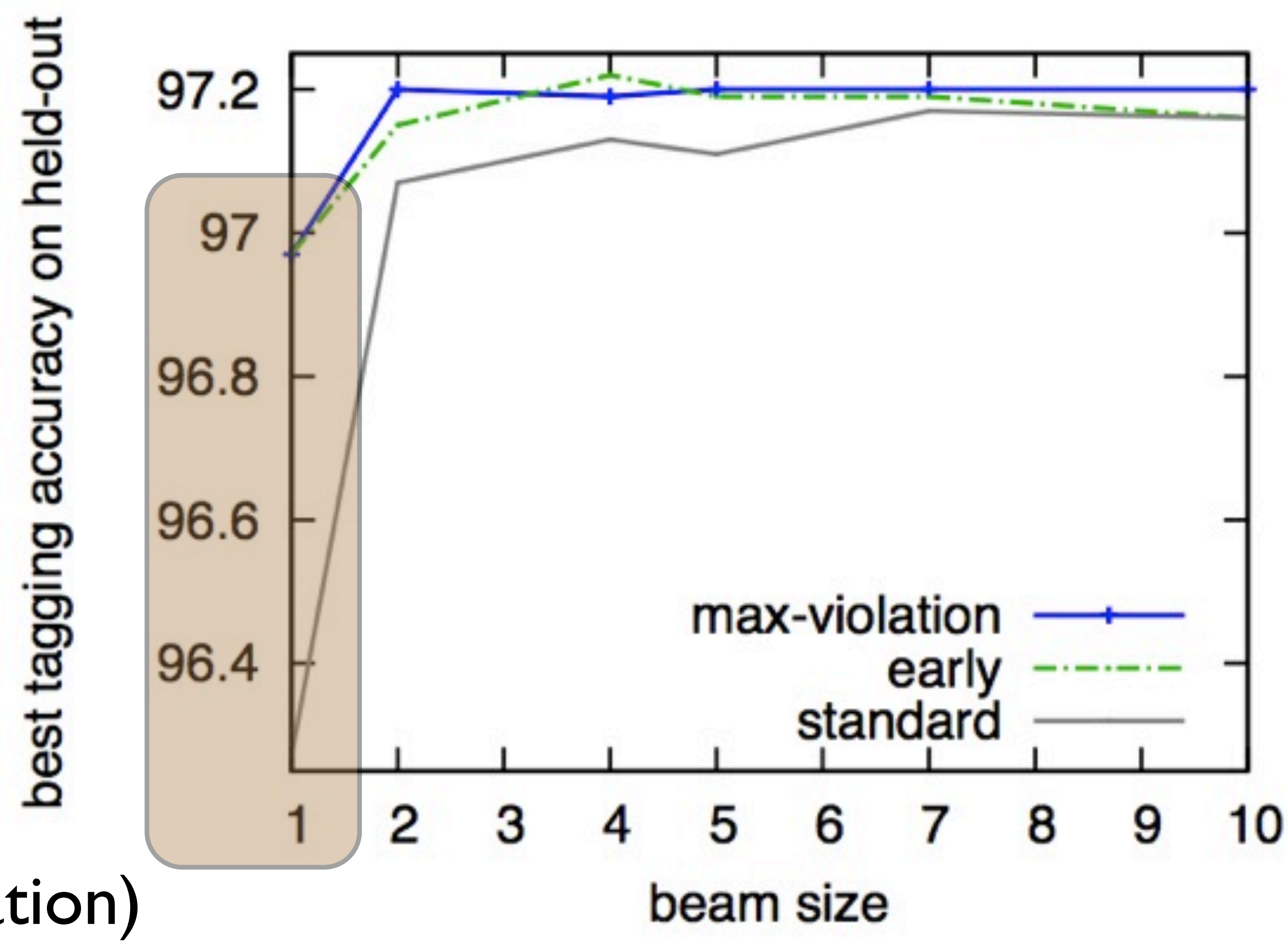
incremental dependency parsing



non-local features,
exact search intractable
(real impact)

1) Trigram Part of Speech Tagging

- standard update performs terribly with greedy search (b=1)
  - because search error is severe at b=1: half updates are bad!
  - no real difference beyond b=2: search error becomes rare

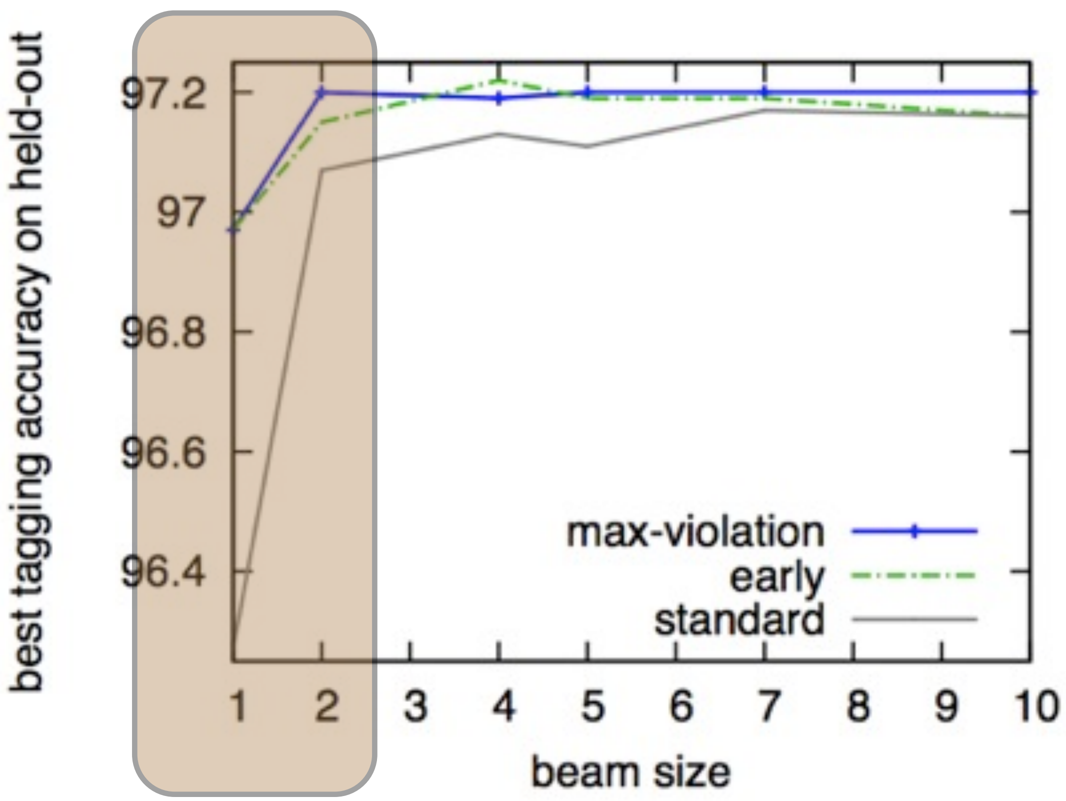


% of bad (non-violation) standard updates

53% 10% 1.5% 0.5%

Max-Violation Reduces Training Time

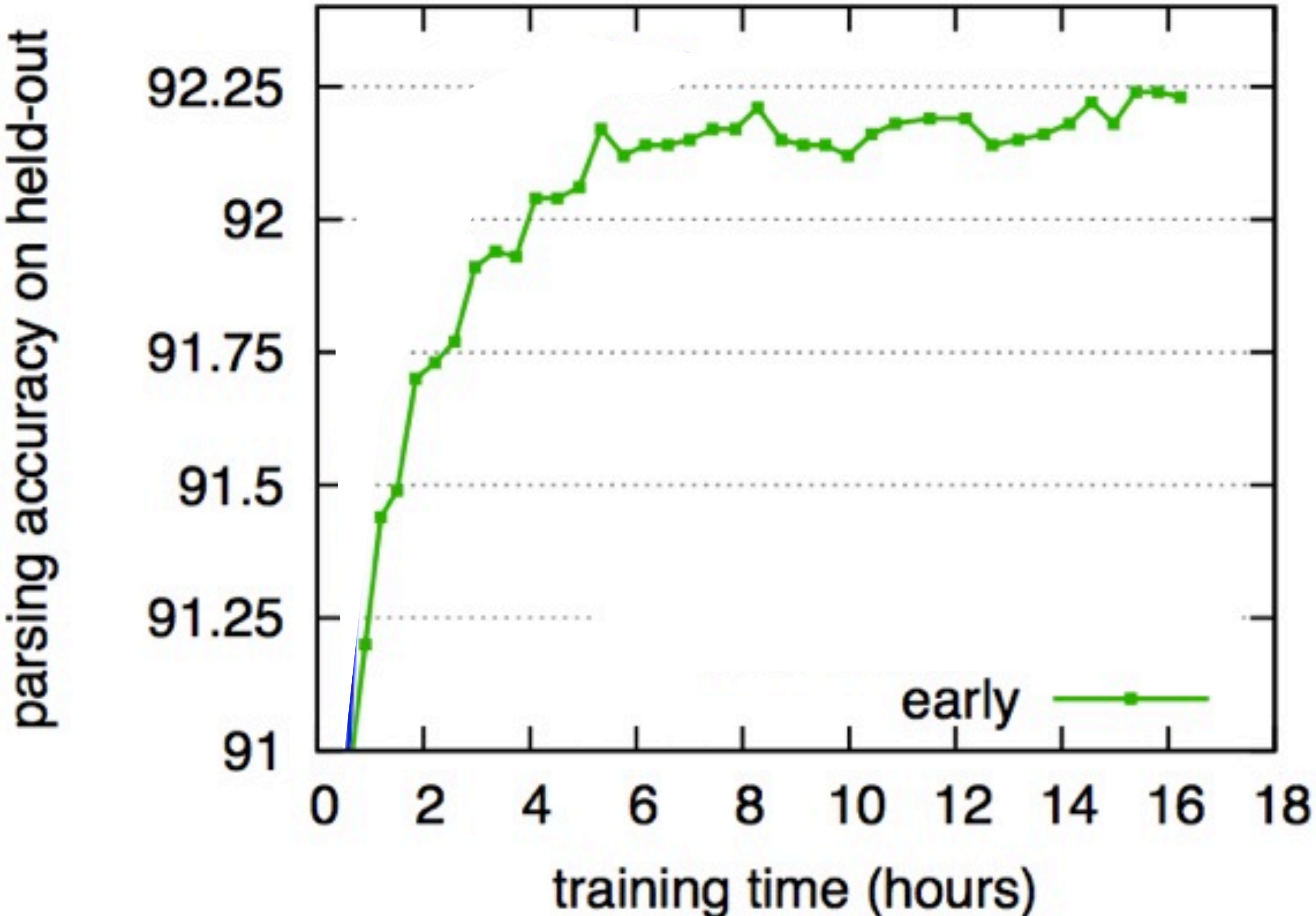
- max-violation peaks at b=2, greatly reduced training time
- early update achieves the highest dev/test accuracy
  - higher than the best published accuracy (Shen et al '07)
- future work: add non-local features to tagging



	beam	iter	time	test
standard	-	6	162m	97.28
early	4	6	37m	97.35
max-violation	2	3	26m	97.33
Shen et al (2007)				97.33

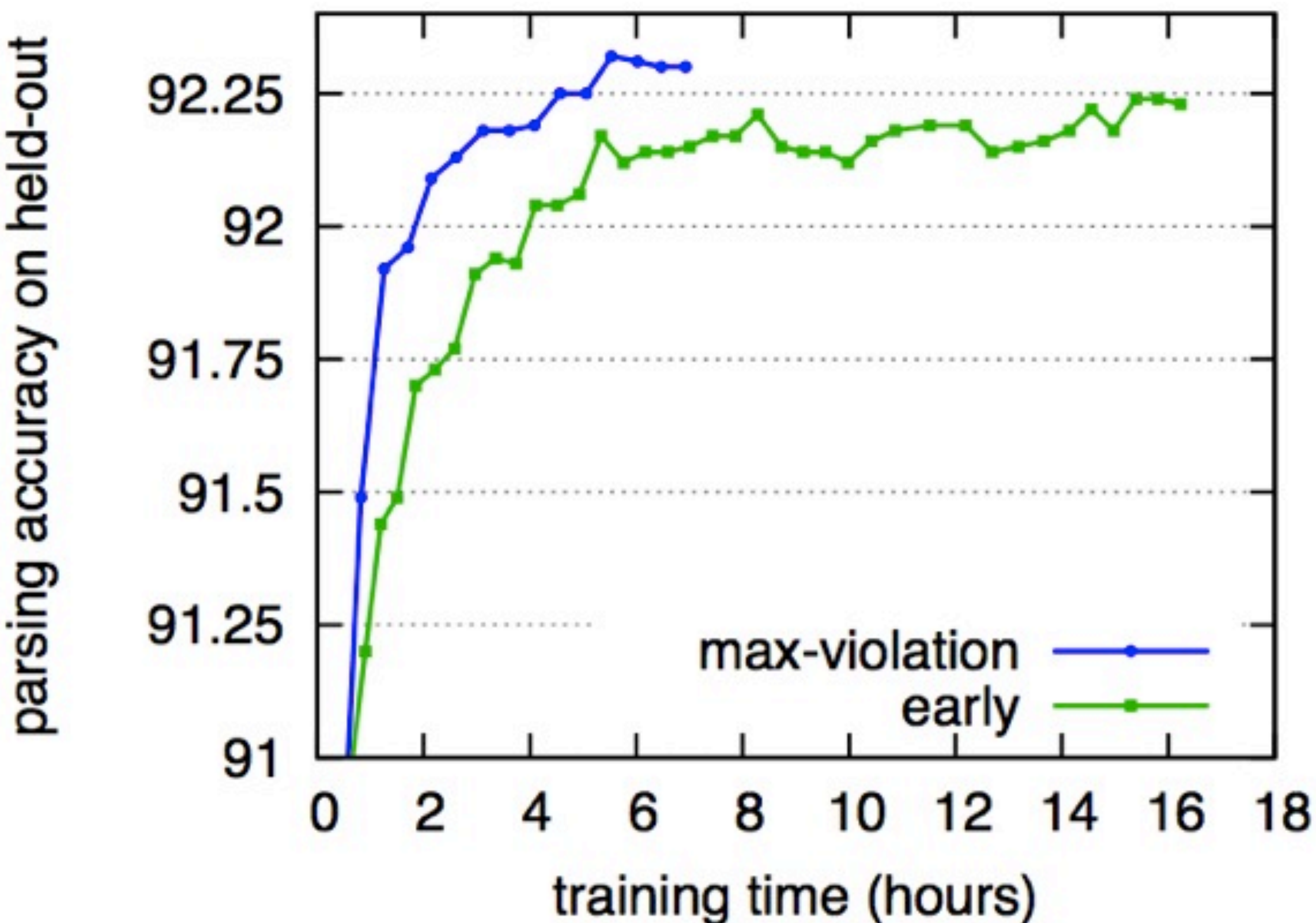
2) Incremental Dependency Parsing

- DP incremental dependency parser (Huang and Sagae 2010)
- non-local history-based features rule out exact DP
  - we use beam search, and search error is severe
  - baseline: early update. extremely slow: 38 iterations



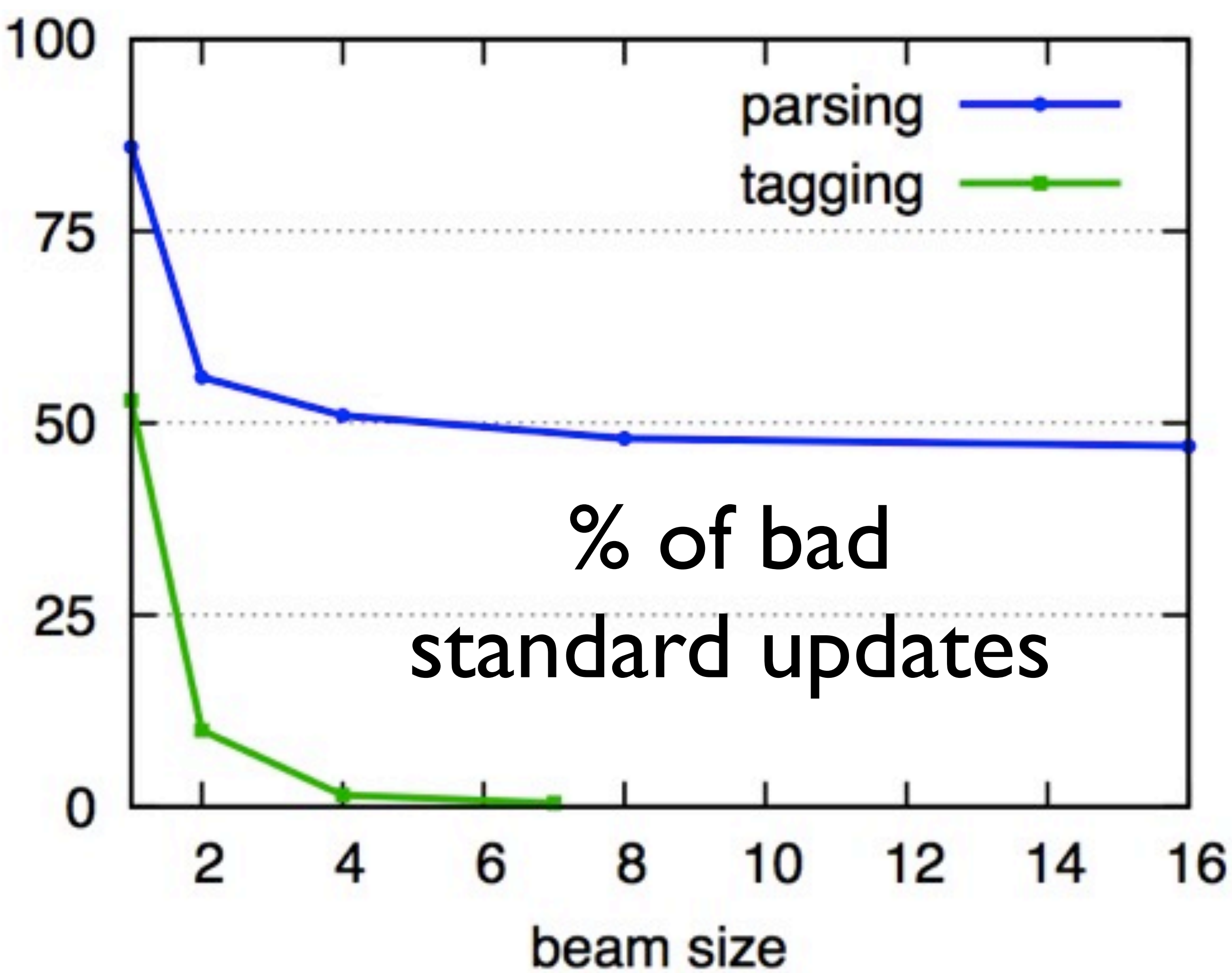
Max-violation converges much faster

- early update: 38 iterations, 15.4 hours (92.24)
- max-violation: 10 iterations, 4.6 hours (92.25)
  12 iterations, 5.5 hours (92.32)



Comparison b/w tagging & parsing

- search error is much more severe in parsing than in tagging
- standard update is OK in tagging except greedy search (b=1)
- but performs horribly in parsing even at large beam (b=8)
    - because ~50% of standard updates are bad (non-violation)!



	test
standard	**79.1**
early	92.1
max-violation	92.2

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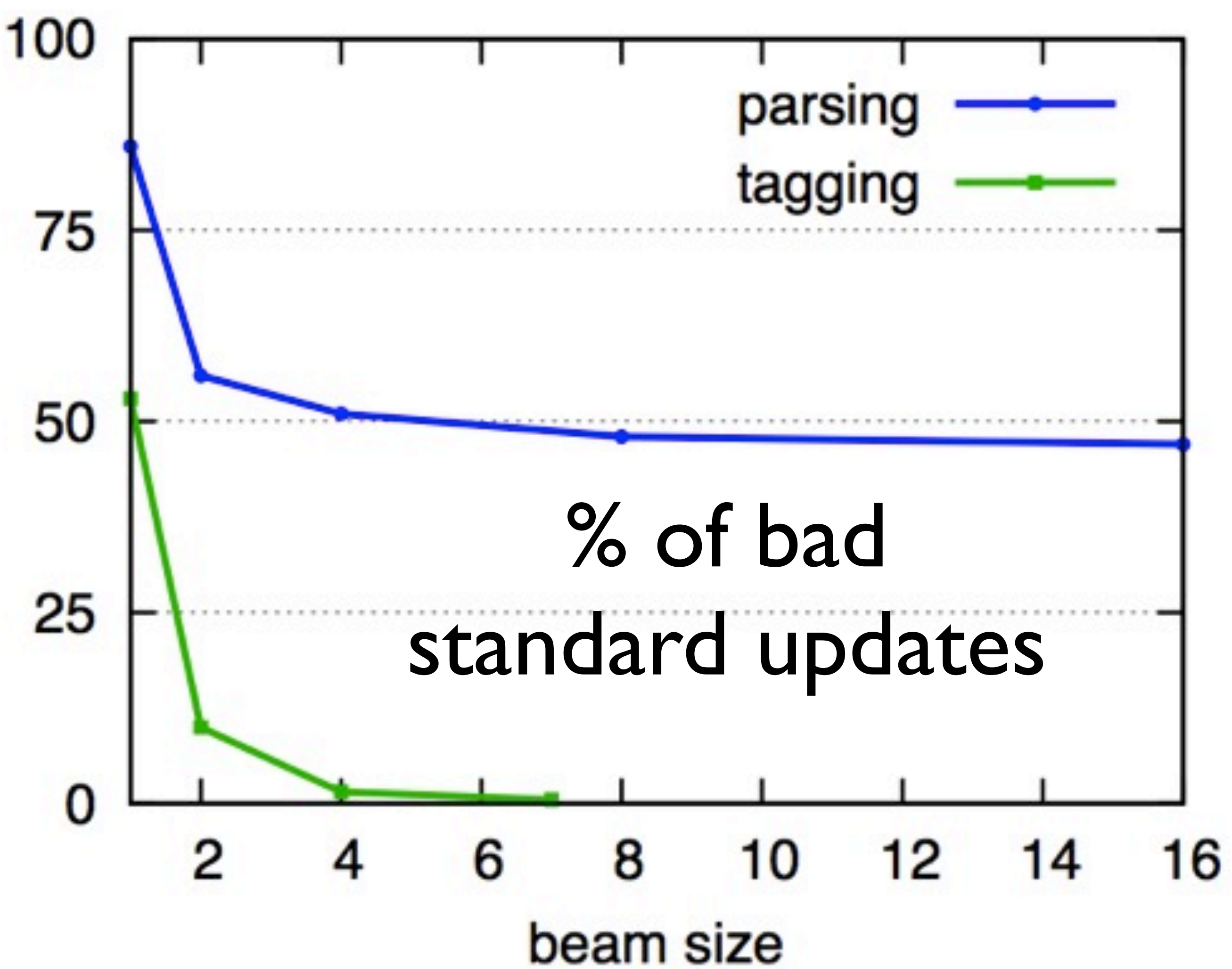

take-home message:
our methods are more helpful
for harder search problems!

	test
standard	**79.1**
early	92.1
max-violation	92.2

Related Work and Discussions

Related Work and Discussions

- our "violation-fixing" framework include as special cases
  - early-update (Collins and Roark, 2004)
  - a variant of LaSO (Daume and Marcu, 2005)
  - not sure about Searn (Daume et al, 2009)

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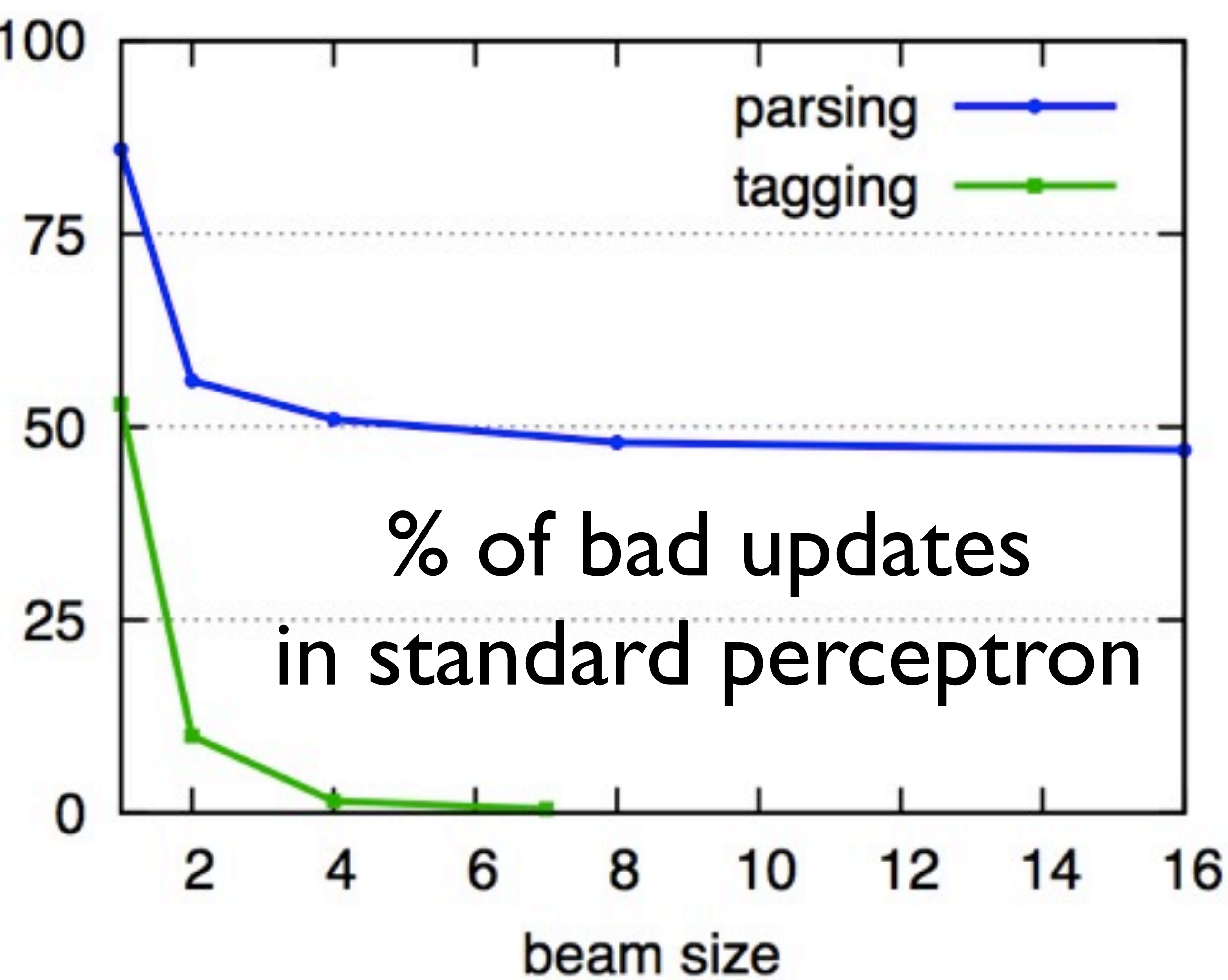
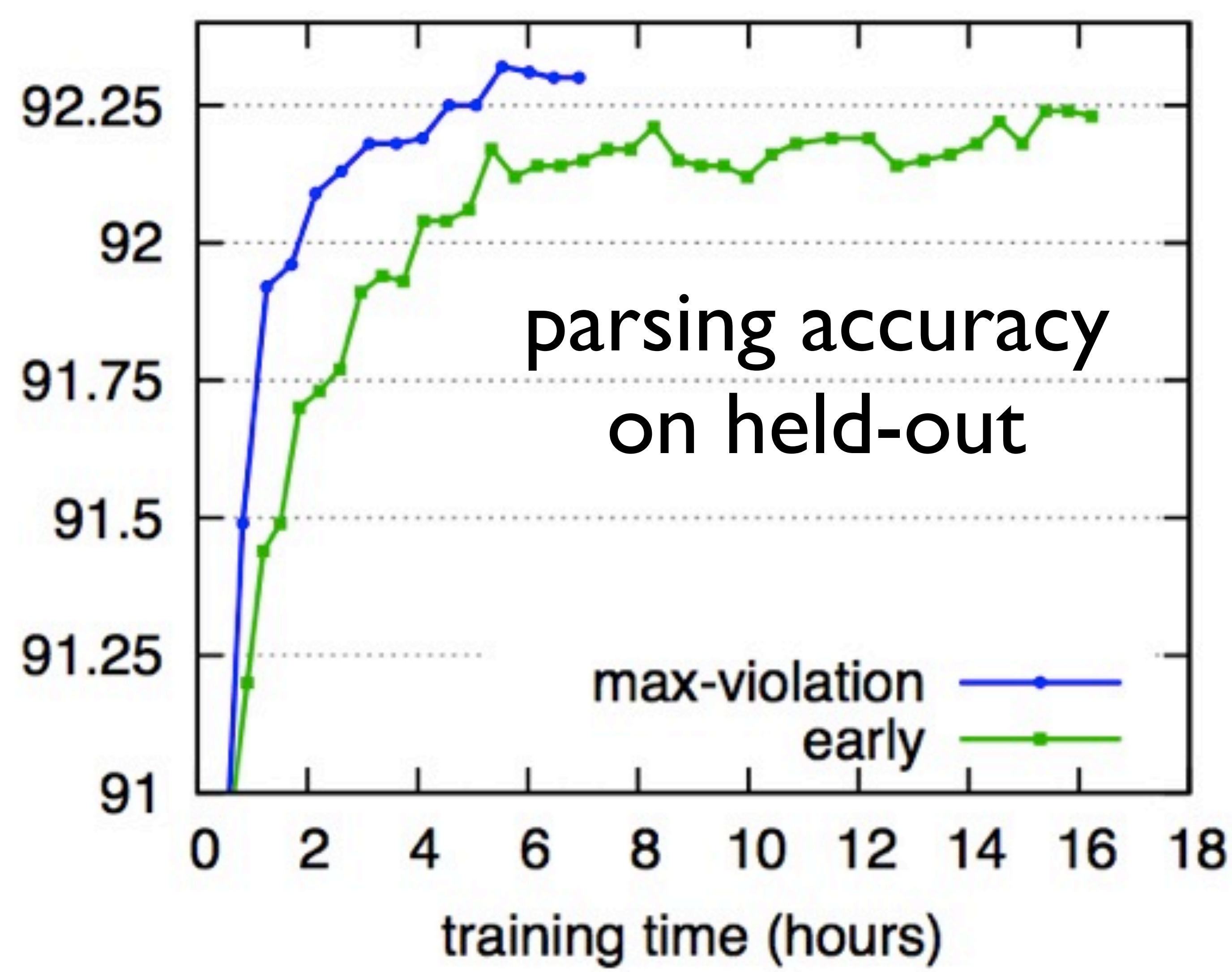
  - but these conditions are too strong to hold in practice
- under-generating (beam) vs. over-generating (LP-relax.)
  - Kulesza & Pereira and Martins et al (2011): LP-relaxation
  - Finley and Joachims (2008): both under and over for SVM

Conclusions

- Structured Learning with Inexact Search is Important
- Two contributions from this work:
  - theory: a general violation-fixing perceptron framework
    - convergence for inexact search under new defs of *separability*
    - subsumes previous work (early update & LaSO) as special cases
  - practice: new update methods within this framework
    - "max-violation" learns faster and better than early update
      - dramatically reducing training time by 3-5 folds
      - improves over state-of-the-art tagging and parsing systems
    - our methods are more helpful to harder search problems! :)

Thank you!





Liang apologizes for not able to come due to visa/passport reasons.

Many thanks to Philipp Koehn for presenting it! Danke!

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